A

Fundamental Constants

The following table gives the values of some frequently used constants.

Symbol	Value	Units	Explanation
a	6,378,137.000	*m*	Semimajor axis of the *WGS-84* ellipsoid
b	6,356,752.314	*m*	Semiminor axis of the *WGS-84* ellipsoid
f	1/298.257	-	Flattening (*WGS-84*, 1987)
g_o	9.80665	m/sec^2	Gravitational acceleration at sea level
μ	3.986030×10^{14}	m^3/sec^2	Earth gravitational constant
l_c	3.2808400	*ft/m*	Length conversion
m_c	2.2046226	*lb/kg*	Mass conversion
R_E	$\sqrt{\mu/g_o}$	*m*	Earth radius
T_E	86164.09886	*sec*	Length of a sidereal day
c_o	$1116.4(1/lc)$	*m/sec*	Sea-level atmospheric sound speed
p_o	$2116.2(g_o l_c^2/m_c)$	N/m^2	Sea-level atmospheric pressure
ρ_o	1.224949119	kg/m^3	Sea-level atmospheric density
π	3.14159256		Mathematical constant
ω	$2\pi/T_E$	*rad/sec*	Earth sidereal rotation rate
ω_E	7.292115×10^{-5}	*rad/sec*	Angular velocity of the Earth
	6076.10	*ft/nm*	Number of feet per nautical mile

B

Glossary of Terms

The following celestial mechanics terms are commonly used in deriving the free flight of ballistic missiles.

Anomaly – An angle; for example, eccentric anomaly, mean anomaly, true anomaly.

- *Eccentric Anomaly* – An angle at the center of an ellipse between the line of apsides and the radius of the auxiliary circle through a point having the same apsidal distance as a given point on the ellipse.
- *Mean Anomaly* – The angle through which an object would move at the uniform average angular speed n measured from the principal focus. Commonly, the angle $n(t - t_o)$ is called the *mean anomaly*, where n is the mean motion.
- *True Anomaly* – The angle at the focus between the line of apsides and the radius vector measured in the direction of orbital motion; the angle measured in the direction in which the orbit is described, starting from perihelion.

Aphelion – The point on an elliptical orbit about the sun that is farthest from the sun.

Apoapsis – The point farthest from the principal focus of an orbit in a central force field.

Apogee – The highest point on an *Earth-centered* elliptical orbit. The point of intersection of the trajectory and its semimajor axis that lies farthest from the principal focus.

Apsides (or Line of Apsides) – In an elliptical orbit, the major axis.

Apsis – The point on a conic where the radius vector is a maximum or a minimum.

Celestial Equator – The great circle on the celestial sphere that is formed by the intersection of the celestial sphere with the plane of the Earth's equator. For solar system applications, it is formed by intersection with the ecliptic.

Celestial Horizon – The celestial horizon of an observer is the great circle of the celestial sphere that is everywhere 90° from the observer's zenith.

Celestial Sphere – A sphere of infinite radius with its center at the center of the Earth upon which the stars and other astronomical bodies appear to be projected. This sphere is fixed in space and appears to rotate counter to the diurnal rotation of the Earth. For solar system navigation purposes, the celestial sphere may be considered to be centered at the Sun.

Colatitude – Defined as 90° – φ, where φ is the latitude.

Coordinates on the Celestial Sphere – Polar coordinates are used in specifying the location of a star or other heavenly body on the celestial sphere. These are the *declination* (δ) and the *right ascension* (*R.A.*).

Declination – The declination of a star is the angular distance north or south, of the celestial equator measured on the celestial sphere.

Earth rate – The angular velocity at which the Earth rotates about its own polar axis. The Earth rate is equal to $15.041°/hr$ or 7.29215×10^{-5} rad/sec.

Ecliptic – The great circle on the celestial sphere that is formed by its intersection with the plane of the Earth's orbit.

Ellipticity – Deviation of an ellipse or a spheroid from the form of a circle or a sphere. The Earth is assumed to have an ellipticity of about 1/297.

Epoch – Arbitrary instant of time for which elements of an orbit are valid.

First Point of Aries (♈) – Vernal equinox.

Geocentric – Pertaining to the center of the Earth as a reference.

Geocentric Coordinates – Coordinates on the celestial sphere as they would be observed from the center of the Earth.

Geodetic Latitude – Geodetic latitude is defined as the angle between the equatorial plane and the normal to the surface of the ellipsoid. It is the latitude commonly used on maps and charts.

Geodesic Line – The shortest line on the curved surface of the Earth between two points. (see also *Great Circle*).

Geographic – Pertaining to the location of a point, line, or area on the Earth's surface.

Gravity – A vertical force acting on all bodies and mass in or around the Earth. The magnitude of the force of gravity varies with location on the Earth and elevation or altitude above mean sea level. This force will cause a free body to accelerate approximately 32.16 ft/sec^2 (or 9.80665 m/sec^2). (Commonly abbreviated by the letter g.)

Great Circle – A circle on the surface of the Earth, the plane of which passes through the center of the Earth, dividing it into two equal parts. A course plotted on a great circle is the shortest distance between two points on the surface of the Earth and is called a geodesic line.

Hour Circle – A great circle of the celestial sphere that passes through the poles and a celestial body.

Hyperbolic Excess Velocity – In the two-body problem, the relative velocity of the bodies after escape from the mutual potential field.

Nadir – The *nadir* is the point of the celestial sphere 180° from the zenith.

North Celestial Pole – This is the point of intersection of the Earth's axis of rotation with the celestial sphere. In solar system navigation applications, the celestial poles form a line normal to the ecliptic plane while preserving the sense of the north–south orientation.

Orbital Elements – The orbit of a body that is attracted by an inverse-square central force can be specified unambiguously by six elements, which are constants of integration from the equations of motion. These parameters (or orbital elements) define an elliptic orbit in space and are as follows: (1) semimajor axis (a), which specifies the size; (2) eccentricity (e), specifies shape and size; (3) time of perigee passage (T), specifies path position at a given time; (4) orbit inclination angle (i), specifies the orientation of the orbital plane to the equatorial plane ($0 \leq i \leq 180°$); (5) longitude of the ascending node (Ω), specifies the angular distance between the first point of Aries (Υ) and the ascending side of the line of nodes; (6) argument of perigee (ω), an angle that specifies the orientation of the ellipse within its own plane. It should be noted that the definition of these elements may differ from those given in books on celestial mechanics. For example, in these books, the *mean longitude, epoch, mean motion*, and *longitude of perihelion* are also included.

Parameters (Orbit) – Orbital elements.

Parameters (Flight) – Descriptive quantities that define the flight conditions relative to a selected reference frame.

Periapsis – In an elliptical orbit, the apses closest to the nonvacant focus. In an open orbit, the point of closest approach to the orbit center.

Perigee – The point in the orbit of a spacecraft that is closest to the Earth when the orbit is about the Earth.

Perihelion – The point of an orbit about the Sun that is closest to the Sun.

Reference, Inertial Space – A system of coordinates that are unaccelerated with respect to the *fixed* stars.

Retrograde – Orbital motion in a direction opposite to that of the planets in the solar system, that is, clockwise as seen from the north of the ecliptic.

Right Ascension (R.A.) – The right ascension of a star is the angle, measured eastward along the celestial equator, from the vernal equinox to the great circle passing through the north celestial pole and the star under observation. Right ascension is frequently expressed in hours, minutes, and seconds of sidereal time (i.e., 1 hour is equal to 15°) because clocks are used in the terrestrial measurement of right ascension.

Sidereal Hour Angle – The sidereal hour angle of a celestial body is the angle at the pole between the hour circle of the vernal equinox and the hour circle of the body, measured westward from the hour circle of the vernal equinox from 0° to 360°.

Sidereal Day – A sidereal day is the interval of time between two successive transits of the vernal equinox over the same meridian.

$$24^h \text{ sidereal time} = 23^h\ 56^m\ 04.1^s \text{ civil time;}$$

conversely,

$$24^h \text{ civil time} = 24^h 03^m 56.6^s \text{ sidereal time.}$$

Time – In astronomical usage, time is usually expressed as universal time (*UT*). This is identical with Greenwich Civil Time and is counted from 0 to 24 hours

beginning with midnight. A decimal subdivision is often used in place of hours, minutes, and seconds. Thus, the following are all identical:
Nov 30.75 *UT*,
Nov 30; $18^h\ 00^m$ *UT*,
Nov 30; 1800 *Z*,
Nov 30; 1:00 *PM EST*.

Topocentric Coordinates – Coordinates on the celestial sphere as observed from the surface of the Earth.

Topocentric Parallax – The difference between geocentric and topocentric positions of a body in the sky.

Vernal Equinox – The point where the Sun appears to cross the celestial equator from south to north. The time of this crossing, when day and night are everywhere of equal length, occurs at about 21 March. Also known as *first point of Aries* and designated by the symbol ♈.

Zenith – The point on the celestial sphere vertically overhead (its direction can be defined by means of a plumb-line).

C

List of Acronyms

A

AA	Air-to-Air (or Anti-Aircraft)
AAA	Antiaircraft Artillery
AAAM	Air-to-Air Attack Management
AAAW	Air-launched Anti-Armor Weapon
AAM	Air-to-Air Missile
AARGM	Advanced Anti-Radiation Guided Missile
AAWS-M	Advanced Antitank Weapons System-Medium
ABICS	Ada-Based Integrated Control System
ABL	Airborne Laser
ABM	Anti-Ballistic Missile (also, Air Breathing Missile)
ABR	Agile Beam fire control Radar (used in the F-16's)
AC^{2}ISR	Airborne Command & Control, Intelligence, Surveillance and Reconnaissance
ADOCS	Advanced Digital Optical Control System
AESA	Active Electronically Scanned Arrays
AEW &C	Airborne Early Warning and Control
AFCS	Automatic Flight Control System
AGM	Air-to-Ground Missile (or Air-launched Surface-attack Guided Missile)
AGNC	Adaptive Guidance, Navigation, and Control
AI	Artificial Intelligence
AIM	Air-Interceptor Missile (or Air-launched Intercept-aerial Guided Missile)
ALCM	Air-Launched Cruise Missile
ALS	Advanced Launch System
AMAS	Automated Maneuvering Attack System
AMRAAM	Advanced Medium-Range Air-to-Air Missile (*AIM-120*)
APT	Acquisition, Pointing, and Tracking
ARM	Antiradiation Radar Missile (also Antiradar Missile)

ASARG Advanced Synthetic Aperture Radar Guidance
ASARS Advanced Synthetic Aperture Radar System (seen as *ASARS-2*)
ASM Air-to-Surface Missile (also, Antiship Missile)
ASRAAM Advanced Short-Range Air-to-Air Missile (*AIM-132*)
ASROC Anti-Submarine Rocket
ASW Antisubmarine Warfare
AT Aerial Target
ATA Automatic Target Acquisition
ATACMS Army Tactical Missile System
ATB Advanced Technology Bomber (e.g., *B-2*)
ATBM Anti-Tactical Ballistic Missile
ATC Automatic Target Cueing
ATCSD Assault Transport Crew System Development
ATF Advanced Tactical Fighter
ATIRCM Advanced Threat Infrared Countermeasures
ATR Automatic Target Recognition
ATT Advanced Tactical Transport
AUV Advanced Unitary Penetrator (warheads used in *CALM*s)
AVMS Advanced Vehicle Management System
AWACS Airborne Warning and Control System

B

BAI Battlefield Air Interdiction
BDA Bomb Damage Assessment
BLU Bomb, Live Unit
BMDO Ballistic Missile Defense Organization
BMEWS Ballistic Missile Early-Warning System
BOL Bearing Only Launch
BPI Boost-phase Intercept
BVR Beyond Visual Range

C

CAD Computer-Aided Design
CAINS Carrier Aircraft Inertial Navigation System
CAS Close Air Support
CASOM Conventionally Armed Stand-Off Missile
CAT Cockpit Automation Technology
CBU Cluster Bomb Unit (e.g., *CBU-97 Sensor Fuzed Weapon*)
C^3I Command, Control, Communications, and Intelligence
C^4ISR Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CCD Charged Couple Device
CCIP Continuously Computed Impact Point
CCV Control Configured Vehicle

CEP	Circular Error Probable
CEPS	Control Integrated Expert Parameter System
CFD	Computational Fluid Dynamics
CG	Command Guidance
CLOS	Command-to-Line of Sight
CM	Countermeasures
CNI	Communication, Navigation, and Identification
CW	Continuous Wave
CWAR	Continuous-Wave Acquisition Radar

D

DEW	Directed-Energy Weapon
DGPS	Differential Global Positioning System
DHEW	Directed High-Energy Weapon
DIRCM	Directed Infrared Countermeasures
DMA	Defense Mapping Agency
DSMAC	Digital Scene-Mapping Area Correlation

E

ECM	Electronic Counter Measures
ECCM	Electronic Counter-Counter Measures
EIS	Electronic Imaging System
ELINT	Electronic Intelligence
EMD	Engineering and Manufacturing Development
EMI/EMP	Electromagnetic Interference/Electromagnetic Pulse
EO	Electro-Optic
EOTS	Electro-Optical Targeting System
ER	Extended Range
ESA	Electronically Steered Antenna
ESAM	Enhanced Surface-to-Air Missile Simulation
EW	Electronic Warfare
ERGM	Extended-Range Guided Munition (e.g., the US Navy's *EX 171*)

F

FAC	Forward Air Controller
FBM	Fleet Ballistic Missile
FBW	Fly-By-Wire
FCS	Flight Control System
FDIR	Fault Detection, Identification, Recovery
FEBA	Forward Edge of Battle Area
FLIR	Forward-Looking Infrared
FMS	Flight Management System
FOV	Field of View

G

GATS/GAM	Global Positioning System-Aided Targeting System/GPS-Aided Munition
GBI	Ground-Based Interceptor
GBU	Guided Bomb Unit
GLCM	Ground-Launched Cruise Missile
GMTI	Ground Moving Target Indication
GNC	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System (the European counterpart of the U.S. *GPS*).
GPS	Global Positioning System
GNC	Guidance, Navigation, and Control
GNSS	Global Navigation Satellite System (the European counterpart of the U.S. *GPS*).
GPS	Global Positioning System

H

HAE	High Altitude, long-Endurance (used in connection with *UAV*s)
HARM	High-speed Anti-Radiation (or Antiradar) Missile
HAW	Homing All the Way
HAWK	Homing All the Way Killer (*MIM-23 SAM*)
HDD	Head-Down Display
HEAP	High-Explosive Armor-Piercing (i.e., a shaped-charge warhead)
HEL	High-Energy Laser
HMD	Helmet-Mounted Display
HMS	Helmet-Mounted Sight
HOBA	High Off-Boresight Angle
HOBS	High Off-Boresight System
HOJ	Home on Jam
HOL	Higher Order Language
HPM	High-Power Microwave
HTK	Hit-to-Kill (this high speed technology destroys targets through direct body-to-body contact)
HUD	Head-Up Display

I

ICAAS	Integrated Control and Avionics for Air Superiority
ICNIA	Integrated Communications Navigation Identification Avionics
IF	Intermediate Frequency
IFF	Identification, Friend or Foe

IFFC	Integrated Flight/Fire Controls
IFPS	Intra-Formation Positioning System
IFTS	Internal Forward-looking infrared and Targeting System
IFWC	Integrated Flight/Weapon Controls
IIR	Imaging Infrared
INS	Inertial Navigation System
I/O	Input/Output
IOC	Initial Operating Capability
IOT&E	Initial Operational Test and Evaluation
IR	Infrared
IRCCM	Infrared Counter-Countermeasures
IRCM	Infrared Countermeasures
IRLS	Infrared Line Scan
IRSS	Infrared Suppressor System
IRST	Infrared Search and Track
IRVAT	Infrared Video Automatic Tracking
ISAR	Inverse Synthetic Aperture Radar (used for target motion detection)
ISR	Intelligence gathering, Surveillance, and Reconnaissance
ITAG	Inertial Terrain-Aided Guidance

J

JASSM	Joint Air-to-Surface Standoff Missile
JAST	Joint Advanced Strike Technology
JDAM	Joint Direct Attack Munition
JDAM-ER	Joint Direct Attack Munitions-Extended Range
JHMCS	Joint Helmet-Mounted Cueing System
J/S	Jamming to Signal Ratio
JSOW	Joint Standoff Weapon
JSTARS	Joint Surveillance Target Attack Radar System
JTIDS	Joint Tactical Information Distribution System

K

KEW	Kinetic Energy Weapon

L

LADAR	Laser Radar, or Laser Amplitude Detection And Ranging
LAIRCM	Large Aircraft Infrared Measures
LANTIRN	Low Altitude Navigation and Targeting Infrared for Night
LASM	Land Attack Standard Missile (a US Navy missile launched from the *DDG 51* destroyers and cruisers)
LASS	Low Altitude Surveillance System
LGB	Laser-Guided Bomb
LLLGB	Low-Level LGB

LOBL Lock-On Before Launch (e.g., *Hellfire AGM-114*)
LOCAAS Low-Cost Autonomous Attack System (note: System is also seen as Submunition)
LOS Line-of-Sight
LOV Low Observable Vehicle
LQG Linear Quadratic Gaussian
LST Laser Spot Tracker

M

MALD Miniature Air Launched Decoy
MAP Mission Area Plan
MaRV Maneuvering Reentry Vehicle
MAWS Missile Approach Warning System
MEAD Multidisciplinary Expert-Aided Design
MEMS Micro-Electro-Mechanical Sensors
MFCRS Multi-Function Control Reference System
MIM Mobile Interceptor Missile
MIMO Multi-Input, Multi-Output
MIRV Multiple Independently targetable Reentry Vehicle
Mk Mark (General Purpose Bomb)
MLRS Multiple-Launch Rocket System
MMS Mission Management System
MMW Millimeter Wave
MR Medium Range
MTI Moving Target Indication (or Indicator)

N

NMD National Missile Defense

O

OAS Offensive Avionics System
OTH Over The Horizon

P

PA Pilot's Associate
PBW Power-By-Wire
PGM Precision-Guided Munition
PTAN Precision Terrain Aided Navigation (used in the TacTom or Tactical Tomahawk missile).
PVI Pilot Vehicle Interface

R

RADAG Radar Area Guidance
RAM Rolling Airframe Missile

RCS	Radar Cross-Section
RESA	Rotating Electronically Scanned Array
RF	Radio Frequency
RFI	Radio Frequency Interference
RHWR	Radar Homing and Warning Receiver
RPV	Remotely Piloted Vehicle
RV	Reentry Vehicle
RWR	Radar Warning Receiver
RWS	Range-While-Scan

S

SACLOS	Semi-Active Command to Line-of-Sight
SAH	Semi-Active Homing
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture radar
SA/SA	Situational Awareness/Situation Assessment
SATCOM	Satellite Communications
SCAD	Subsonic Cruise Armed Decoy
SDB	Small-Diameter Bomb
SDI	Strategic (or Space) Defense Initiative
SEAD	Suppression of Enemy Air Defenses
SFW	Sensor Fuzed Weapon (i.e., this is an unguided gravity weapon)
SIGINT	Signal Intelligence (also seen as *Sigint*)
SLAM	Standoff Land-Attack Missile
SLAM-ER	Standoff Land-Attack Missile – Expanded Response
SLBM	Submarine (or Sea)-Launched Ballistic Missile
SLCM	Sea-Launched Cruise Missile
SNR	Signal-to-Noise Ratio
SOF	Special Operations Forces
SRAM	Short-Range Attack Missile
SSBXR	Small Smart Bomb Extended Range (a *JDAM* spin-off)
SSGNs	Nuclear-powered Guided-missile submarines
SSNs	Nuclear-powered attack submarines
SSST	Supersonic Sea-Skimming Target
START	Strategic Arms Reduction Treaty
STOL	Short Take-Off and Landing
STOVL	Shorts Take-Off and Vertical Landing

T

TADS	Terrain Awareness and Display System
TAINS	*TERCOM*-Aided Inertial Navigation System
TAMD	Theater Air and Missile Defense
TAN	Terrain-Aided Navigation
TAP	Technology Area Plan

TAWS Terrain Awareness and Warning System, or
Theater Airborne Warning System (this is an *IR* capability)
TBM Theater Ballistic Missile (also called Tactical Ballistic Missile)
TERCOM Terrain-Contour Matching
TERPROM Terrain Profile Matching
TFLIR Targeting Forward-Looking Infrared
TFR Terrain-Following Radar
TF/TA² Terrain Following/Terrain Avoidance/Threat Avoidance
TGSM Terminally Guided Sub-Munition
TGW Terminally Guided Warhead
THAAD Theater High Altitude Area Defense
TIALD Thermal Imaging Airborne Laser Designator
TIAS Target Identification and Acquisition System
TLAM Tomahawk Land Attack Missile
TMD Theater Missile Defense (also: Tactical Munitions Dispenser)
TOW Tube-launched, Optically-tracked, Wire-guided
TRAM Target-Recognition Attack Multisensor
TSS Target Sight System (uses focal plane array *FLIR* and *LST*)
T-UAV Tactical Unmanned Aerial Vehicle
TVC Thrust Vector Control
TVM Track-Via-Missile
TWS Track-While-Scan (a multiple target tracking radar)

U

UAV Unmanned Aerial (or Air) Vehicle
UCAV Unmanned Combat Air Vehicle (also seen as "Uninhabited Combat Aerial Vehicle")
UHF Ultra High-Frequency
URAV Unmanned Reconnaissance Air Vehicle
URV Unmanned Research Vehicle
USW Undersea Warfare

V

VCATS Visually-Coupled Acquisition and Targeting System
VHSIC Very High Speed Integrated Circuit
VLS Vertical Launch System
VLSI Very Large Scale Integration
VMS Vehicle Management System
VR Virtual Reality
VSIM Virtual Simulator
VSTOL Vertical/Short Takeoff and Landing
VTAS Visual Target Acquisition System

W

WCMD Wind Corrected Munitions Dispenser
WGS World Geodetic System
WMD Weapons of Mass Destruction
WVR Within Visual Range

D

The Standard Atmospheric Model

For computing drag and thrust, it is necessary to know, as functions of altitude, the Earth's atmospheric pressure, density, and speed of sound. These functions follow from the so-called *ARDC* (Air Research and Development Command, of the U.S. Air Force) model atmosphere, a more accurate model than those used previously (e.g., RAND model). The *ARDC* model assumes that the air from sea level up to an altitude of roughly 300,000 ft (91,440 m) is of constant molecular weight and consists of six concentric layers.

In this appendix, the *ICAO* (International Civil Aviation Organization) standard atmosphere model is used as the flight environment for missiles.

At Sea Level

$T_o =$ temperature (288.1667) [kelvin]
$P_o =$ static pressure (101314.628) [N/m^2]

At altitude z, an approximation to the standard atmosphere is used. The atmosphere is divided into three zones as follows:

(1) $z \leq 11,000\,m$,
(2) $1,000\,m < z \leq 25,000\,m$,
(3) $z > 25,000\,m$.

Different formulas are used to find the ambient atmospheric temperature and pressure, T_a and P_a, in each of the zones.

Zone 1: $z \leq 11,000\,m$

$$T_a = T_o - (0.006499708)z \quad [K], \tag{D.1}$$

$$P_a = P_o(1 - 2.255692257 \times 10^{-5}\, z)^{5.2561} \quad [N/m^2], \tag{D.2}$$

Zone 2: $11,000\,m < z \leq 25,000\,m$,

$$T_a = 216.66666667 \quad [K], \tag{D.3}$$

$$P_a = P_o(0.223358)\{\exp[-1.576883202 \times 10^{-4}(z - 11000)]\}\ [N/m^2]. \tag{D.4}$$

Zone 3: $z > 25,000\,m$,

$$T_a = 216.66666667 + (3.000145816 \times 10^{-3})(z - 25000) \;\; [K], \tag{D.5}$$

$$P_a = (2489.773467)\{\exp[-1.576883202 \times 10^{-4}(z - 25000)]\} \; [N/m^2]. \tag{D.6}$$

In all three zones, the ambient atmospheric density and the speed of sound are given by

$$\rho_a = P_a/RT_a \;\; [kg/m^3], \tag{D.7}$$

$$V_a = 20.037673\sqrt{T_a} \;\; [m/sec], \tag{D.8a}$$

where R is the gas constant (286.99236 [(N-m)/(K_p-K)]. Note that the speed of sound V_a, can also be calculated from the relation

$$V_a = kRT, \tag{D.8b}$$

where

k = the ratio of specific heat of the gas (= 1.4 for air),
R = gas constant (= 286.99236[(N-m)/(Kp -°K)]),
T = absolute temperature for the standard atmosphere.

ICAO Standard Atmosphere Input/Output:

The input to the atmosphere model is

z = altitude of interest [m].

The output from the model is

T_a = ambient atmospheric temperature at altitude z [K],
P_a = ambient atmospheric pressure at altitude z [N/m^2],
ρ_a = ambient atmospheric density at altitude z [kg/m^3],
V_a = speed of sound at altitude z [m/sec].

While not a factor in some studies, altitude can be an important consideration. As altitude increases, density decreases, leading to a lower dynamic pressure for a given speed. This leads to lower drag, so that missile deceleration is less pronounced, but it also leads to lower moments and forces, so the missile loses some maneuverability. Also, since the speed of sound is a function of altitude, the missile Mach number for a given speed depends on altitude. Missile aerodynamic properties (e.g., drag coefficient, lift coefficient, and moment coefficient) depend on Mach number and so will change with altitude, giving different missile aerodynamic responses.

Pressure, temperature, air density, and speed of sound are calculated using pressure curve fits and temperature gradients derived from the 1962 standard atmosphere data. The input altitude and the calculated atmospheric conditions are all in metric units. Four data tables of the 1962 U.S. standard atmosphere data are used to calculate the atmosphere parameters: temperature, temperature gradient, pressure, and corresponding reference altitudes. Table D.1 shows these four data tables combined [1]. These tables are referenced using altitudes expressed in geopotential meters. One geopotential meter is defined as the vertical distance through which a one-kilogram mass must be moved to increase its potential energy by 9.80665 joules [2]. Thus, a given input altitude h in geometric meters is converted to altitude H in geopotential meters using the expression [2]

$$H = [R_E/(R_E + h)]h, \tag{D.9}$$

where

H = geopotential altitude,
h = geometric altitude,
R_E = radius of the Earth = 6, 356, 766 m corresponding to 45° latitude on a nonperfect spherical Earth model.

Table D.1. *1962 U.S. Standard Atmosphere* Data Tables

Altitude H [m]	Temperature T [K]	Temp. Gradient ΔT [K]	Pressure P [N/m^2]
0.0	288.15	– 0.0065	101325.000
11,000.0	216.65	0.0	22632.000
20,000.0	216.65	0.0010	5474.8700
32,000.0	228.65	0.0028	868.0140
47,000.0	270.65	0.0	110.9050
52,000.0	270.65	– 0.002	59.0005
61,000.0	252.65	– 0.004	18.2099
79,000.0	180.65	0.0	1.0377
90,000.0	180.65	0.003	0.16438
100,000.0	210.65	0.005	3.0075E-2
110,000.0	260.65	0.010	7.3544E-3
120,000.0	360.65	0.020	2.5217E-3
150,000.0	960.65	0.015	5.0617E-4
160,000.0	1110.65	0.010	3.6943E-4
170,000.0	1210.65	0.070	2.7926E-4
190,000.0	1350.65	0.005	1.6852E-4
230,000.0	1550.65	0.004	6.9604E-5
300,000.0	1830.65	0.0033	1.8838E-5
400,000.0	2160.65	0.0026	4.0304E-6
500,000.0	2420.65	0.0017	1.0957E-6
600,000.0	2590.65	0.0011	3.4502E-7
700,000.0	2700.65	0.0	1.1918E-7

As stated in the beginning of this appendix, the *ARDC* model atmosphere assumes that the air from sea level to roughly 300,000 ft consists of six concentric layers. Within each layer, the gradient of the absolute temperature τ with respect to the geopotential altitude H is assumed constant. From (D-9), the gradient $d\tau/dH$ within each layer is given in Table D.2.

Table D.2. Absolute Temperature Gradient for Different Layers

Layer	Gradient ($d\tau/dH$) [°*R/ft*]	Altitude Range [*ft*]
I	-3.566×10^{-3}	$0 < H < 36,089$
II	0	$36,089 < H < 82,021$
III	1.646×10^{-3}	$82,021 < H < 154,199$
IV	0	$154,199 < H < 173,885$
V	-2.469×10^{-3}	$173,885 < H < 259,186$
VI	0	$259,186 < H < 295,276$

The air density ρ decreases exponentially with altitude within the isothermal layers. That is,
Layers II, IV, VI:

$$\rho = C_1\, e^{-pH}. \tag{D.10}$$

Layers I, III, V:

$$\rho = C_2 \tau^{-k}, \tag{D.11}$$

where C_1, C_2, p, and k are constant within a given layer.

Table D.3 shows documented atmospheric data for a 1976 U.S. standard atmosphere in metric units [3].

Table D.3. *1976 U.S Standard Atmosphere* Data in Metric Units

Geopotential Altitude [*m*]	Pressure [N/m^2]	Density [kg/m^3]	Speed of Sound [*m/sec*]	Temperature [*K*]
0.0	101,325.0	1.2250	340.3	288.2
5,000.0	54,019.0	0.73612	320.5	255.7
10,000.0	26,436.0	0.41271	299.5	223.2
15,000.0	12,044.0	0.19367	295.1	216.7
20,000.0	5,475.0	0.088035	295.1	216.7

References

1. *Handbook of Chemistry and Physics*, 55th edition, Chemical Rubber Company, 1974, page F-191.
2. *Handbook of Geophysics and Space Environment*, 1985, pp.14–17.
3. *Airplane Aerodynamics and Performance*, Roskam Aviation and Engineering Corporation, 1981, page 13.

E

Missile Classification

In much the same manner as aircraft, missiles are typed by their general characteristic grouping. Such a grouping may show in what manner a missile is used, but it will not identify a particular missile. This general classification makes use of three items: (1) launch environment, (2) target environment (or mission), and (3) type of vehicle. These classifications will now be discussed in more detail.

Launch Environment: Launch environment may be air, ground, underground, or underwater. Thus the letters are ***A*** for air, ***G*** for ground, ***L*** for underground, and ***U*** for underwater. A more complete designation of missile launch environments is as follows:

A - Air
B - Multiple
C - Coffin
F - Individual
G - Ground
H - Silo stored
L - Silo launched
M - Mobile
P - Soft pad
R - Ship
U - Underwater.

Examples of this general classification are as follows:

AIM - Air-Interceptor Missile
AGM - Air-to-Ground (or Surface) Missile
LGM - Silo-launched Surface-to-Surface Missile
UGM - Underwater-to-Surface Missile.

A more typical example is as follows:

ADM - 20***A***,

where ***A*** implies "air," ***D*** "decoy," ***M*** "guided missile," the 20 implies the "20th design," and *A* the "A series."

Target Environment (or Mission): The second letter is used to designate the target environment or mission. This letter may be ***I*** for interceptor, ***G*** for surface target, or ***Q*** for drone. The complete mission designation symbols are as follows:

D - Decoy
E - Special electronic
G - Surface attack
I - Intercept
Q - Drone
T - Training
V - Underwater attack
W - Weather.

Type of Vehicle: The third letter designates the type vehicle as follows:

M - Guided missile
N - Probe
R - Rocket.

Status: The status designation symbols are as follows:

J - Special test, temporary
N - Special test, permanent
X - Experimental
Y - Prototype
Z - Planning.

In addition to the general designator for missile identification, additional items of information may be included as follows:

1. Status prefix
2. Launch environment
3. Primary mission
4. Vehicle type
5. Vehicle design number
6. Vehicle series
7. Manufacturer's code
8. Serial number.

More specifically, missile designators, when the occasion warrants, will have a status prefix symbol but not necessarily a launch environment symbol. For example, a typical designator is shown below for an early *Minuteman* missile (***JLGM-30BO03***). Note that it contains eight items of essential information:

J - Status prefix
L - Launch environment
G - Mission symbol
M - Vehicle type symbol
30 - Design number
B - Series symbol
BO - Manufacturer's code
03 - Serial number.

Tables E.1 through E.3 give more complete designations.

Table E.1 shows the various methods of protecting, storing, and launching a military rocket or guided missile. Rocket systems employed for line-of-sight (LOS) fire against ground targets are not included. Some typical examples of missile designators are given in this table.

Note that several missiles are designed for similar tasks; only the method of launching differs. This similarity is noted by the second symbol with the missile designator. These tasks or missions are given in Table E.2 along with their characteristic identifying letter and description.

Table E.1. Launch Environment Symbols

1st Letter	Title	Description	Example
A	Air	Launched from aircraft while in flight.	*AGM-45A* (Shrike)
B	Multiple	Capable of being launched from more than one environment.	*BQM-34A* (Firebee)
C	Coffin	Horizontally stored in a protective enclosure and launched from the ground.	*CGM-13B* (Mace)
F	Individual	Carried by one man.	*XFIM* (Redeye)
H	Silo Stored	Vertically stored below ground level and launched from the ground.	*HGM-25A* (Titan)
L	Silo Launched	Vertically stored and launched from below ground level.	*LGM-30G* (Minuteman III)
M	Mobile	Launched from a ground vehicle or movable platform.	*MIM-23A K* (Hawk)
P	Soft Pad	Partially or nonprotected in storage and launched from the ground.	*PGM-17A* (Thor)
R	Ship	Launched from a surface vessel such as a ship or barge.	*RIM-46A* (Sea Mauler)
U	Underwater	Launched from a submarine or other underwater device.	*UGM-27C* (Polaris)

Table E.3 shows the types of vehicles that have a combat-related mission. The last two items of a missile designator are the design number and series symbol. The same design number identifies each vehicle type of the same basic design. Where more than one design is present for a single vehicle type, consecutive design numbers are assigned. When major modifications are present in a vehicle type, then a sequential

Table E.2. *Mission* Symbols

2nd Letter	Title	Description	Example
D	Decoy	Vehicles designed or modified to confuse, deceive, or divert enemy defenses by simulating an attack vehicle.	*ADM-20A* (Quail)
E	Special Electronic	Vehicles designed or modified with electronic equipment for communications, countermeasures, electronic radiation sounding, or other electronic recording or relay missions.	*XFEM-43B* (Redeye)
G	Surface Attack	Vehicles designed to destroy enemy land or sea targets.	See Table E-1
I	Intercept-Aerial	Vehicles designed to intercept aerial targets in defensive or offensive roles.	*AIM-9E* (Sidewinder)
Q	Drone	Vehicles designed for target, reconnaissance, or surveillance purposes.	*BQM-34A* (Firebee)
T	Training	Vehicles designed or permanently modified for training purposes.	*ATM-12B* (Bullpup)
U	Under water Attack	Vehicles designed to destroy enemy submarines or other underwater targets.	*UUM-44A* (SUBROCK)
W	Weather	Vehicles designed to observe, record, or relay data pertaining to meteorological phenomena.	*PWN-5A*

letter (e.g., *A*, *B*) indicates each modification. For example, the latest version (as of this writing) or modification of the *Sidewinder* air interceptor missile is the *AIM-9X* (see Table F.2).

In addition to the launch environment, mission, and vehicle type, the status is also used (see also Appendix F). The status prefix designations are listed in Table E.4.

Table E.4 presents the joint electronics type designation system (*JETDS*) used in US military electronic equipment. An example for this type of designation is shown below.

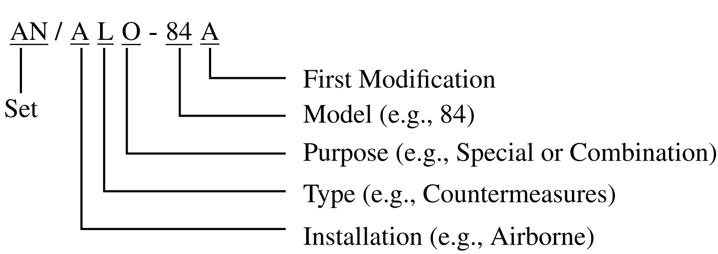

Table E.3. Vehicle Type Symbols

3rd Letter	Title	Description	Example
M	Guided Missile	As the third letter in a missile designator, it identifies an unmanned, self-propelled vehicle. Such a vehicle is designed to move in a trajectory or flight path that may be entirely or partially above the Earth's surface. While in motion, this vehicle can be controlled remotely or by homing systems, or by inertial and/or programmed guidance from within. The term "guided missile" does not include space vehicles, space boosters, or naval torpedoes, but it does include target and reconnaissance drones.	See Table E.2
N	Probe	The letter *N* is used to indicate nonorbital-instrumented vehicles that are not involved in space missions. These vehicles are used to penetrate the space environment and transmit or report back information.	None
R	Rocket	This identifies a self-propelled vehicle without installed or remote control guidance mechanism. Once launched, the trajectory or flight path of such a vehicle cannot be changed.	*AIR-2B* (Super Genie)

Aerial Targets, Drones, and Decoys:

We conclude this appendix by listing some of the better-known *aerial targets* and *decoys*.

MQM-107D/E Streaker:

This is a jet-powered recoverable, variable-speed target drone. The third-generation *D* model is a recoverable, variable-speed target drone used for *RDT&E* (research, development, test, and evaluation) and weapon system evaluation, while the fourth-generation *E* model with improved performance is now operational. The guidance and control system is either underground control or preprogrammed flight, and has high-*g* autopilot provisions. The *MQM-107D/E*'s speed is 230–594 mph, operating at an altitude of 50–40,000 ft, with an endurance of 2 hr, 15 min. The *IOC* (initial operating capability) was in 1987.

Table E.4. Status Prefix Symbols

Letter	Title	Description
J	Special Test, Temporary	Vehicles on special test programs by authorized organizations and vehicles on bailment contract having a special configuration to accommodate the test. At completion of the test, the vehicles will be either returned to their original configuration or returned to standard operational configuration. Example: *J85-GE-7* turbojet engine.
N	Special Test, Permanent	Vehicles on special test programs by authorized activities and vehicles on bailment contract whose configurations are so drastically changed that return of the vehicles to their original configurations is beyond practicable or economical limits.
X	Experimental	Vehicles in a developmental or experimental stage, but not established as standard vehicles for service use. Example: Army's *Nike Zeus XLIM-49A*.
Y	Prototype	Preproduction vehicles procured for evaluation and test of a specific design.
Z	Planning	Vehicles in the planning or predevelopment stage.

BQM-34A Firebee:

The *Firebee* is also a jet-powered, variable-speed, recoverable target drone. Initial development of the *BQM-34A* drones was in the early 1950s (*IOC* was circa 1951), and was used to support weapon system and *RDT&E* (research, development, test, and evaluation). A microprocessor flight control system provides a prelaunch and in-flight test capability. The guidance and control methods include choice of radar, radio, active seekers, and an automatic navigator. The maximum speed of the *BQM-34A* drone is 690 mph at 6,500 ft. Current *BQM-34A*s have been updated with General Electric *J85-100* engines, and are used for weapon system evaluation. The latest version of the *Firebee* is the *BQM-34 M/L*.

BQM-74C:

These target drones were used as decoys during the Persian Gulf War.

Q-4:

The *QF-4* is a converted, remotely piloted *F-4 Phantom* fighter aircraft, used for full-scale training and/or testing purposes. The *QF-4* replaces the *QF-106* as a joint

Table E.5. Joint Electronics Type Designation System

Installation		Type		Purpose	
A	Piloted Aircraft	*A*	Invisible light, heat radiation	*B*	Bombing
B	Underwater mobile sub-marine	*C*	Carrier	*C*	Communications
D	Pilotless carrier	*D*	Radiac	*D*	Direction finder, reconnaissance and/or surveillance
F	Fixed ground	*G*	Telegraph or teletype	*E*	Ejection and/or release
G	General purpose use	*I*	Interphone and public address	*G*	Fire-control or Searchlight directing
K	Amphibious	*J*	Electromechanical or Inertial wire covered	*H*	Recording and/or Reproducing
M	Mobile (ground)	*K*	Telemetering	*K*	Computing
P	Portable	*L*	Countermeasures	*M*	Maintenance and/or Test assemblies
S	Water	*M*	Meteorological	*N*	Navigation aids
T	Transportable (ground)	*N*	Sound in air	*Q*	Special or combination of purposes
U	General utility	*P*	Radar	*R*	Receiving, passive detecting
V	Vehicular (ground)	*Q*	Sonar and underwater sound	*S*	Detecting and/or range and bearing
W	Water surface and under water combination	*R*	Radio	*T*	Transmitting
Z	Piloted–pilotless vehicle combination	*S*	Special or combinations of types	*W*	Automatic flight or Remote control
		T	Telephone (wire)	*X*	Identification and Recognition
		V	Visual and visible light		
		W	Armament		
		X	Facsimile or television		
		Y	Data processing		

service full-scale aerial target, and uses an improved flight control system and has a greater payload. Guidance of the *QF-4* consists of multifunction command-and-control multilateration system.

QF-106:

The *QF-106* is a converted, remotely piloted Convair *F-106A Delta Dart* fighter used for full-scale training or testing. With a service ceiling of 50–55,000 ft, the *QF-106* has a range of 575 miles. Its power plant is a 24,500 lb thrust (with afterburning) Pratt & Whitney *J75-P-17* turbojet.

In addition to the aerial targets and decoys, there are a number of *reconnaissance and surveillance* aircraft:

RQ-1A, B, L Predator:

This is a medium-altitude, long-endurance *UAV* (unmanned aerial vehicle), flown remotely and controlled from the ground. It is envisioned primarily as a reconnaissance platform. More specifically, the *Predator* is a fire-and-forget, inertial guided system designed to strike targets from 17 m (55.78 ft) to 600 m (1968.6 ft) either by direct attack or by flying over the target and shooting at the most vulnerable aspect in an attack profile, known as fly-over, shoot-down mode. Navigation is accomplished by *GPS/INS*. It cruises at 75 mph (it can reach 90 mph) an altitude of 10,000–15,000 ft (with a ceiling of 25,000 ft), and has a range of about 500 nm. Note that the *Predator* must fly as high as 25,000 ft to avoid shoulder-fired weapons. Moreover, the *Predator* can cover mobile targets from a 15,000-ft slant range for at least 24 hours. This *UAV* has already demonstrated its capability during surveillance missions over Bosnia and in Operation Allied Force in the skies above Kosovo, Yugoslavia, where it collected intelligence data and searched for targets. The *Predator* can stay in the air for 40 hours, loitering over dangerous areas, and is equipped with *EO/IR* and *SAR* sensors with a K_u-band (12–18 GHz range) satellite data link allowing real-time transmissions of video images to a ground station (i.e., it sends back real-time video images to commanders of what it is observing). In the Afghanistan conflict, live video was transferred from the *Predator* (*RQ-1B*) to *AC-130 gunships* and real-time retargeting of heavy bombers. The *Predator* can also spot buried land mines, even newer plastic versions that elude other radars. Pilots fly the aircraft remotely from vans at their base, using controls found in a normal cockpit. (Note that one problem with controllers mentioned is the limited field of view.)

More recently, the Air Force's *Predator UAV* program is beginning to evolve from a nonlethal reconnaissance asset to an armed, highly accurate tank-killer. On February 16, 2001, an inert *Hellfire-C* (for more information on the *Hellfire* missile see Table F.3) laser-guided missile using its *LOS* communication band and *IR* laser-ball was successfully launched from a *Predator UAV* at the Nellis AFB, Nevada. It aimed and struck the turret of a stationary tank from an altitude of 2,000 ft (610 meters) and a range of 3 miles (4.83 km) as part of a Phase I feasibility demonstration. On February 21, 2001, two more successful test launches were made. The *Predator* successfully aimed and launched a live *Hellfire-C* laser-guided missile that struck an unmanned stationary Army tank. General Atomics Aeronautical Systems, Inc. redesigned two of its *UAV*s as *Predator-Bs (MQ-9)* with a turboprop engine. The enhanced aircraft would be able to carry eight *Hellfire* missiles, rather than only two in the current system. It would also fly several times faster and could reach an altitude of 45,000–52,000 ft. Phase II of the program will take the *Predator–Hellfire* combination to more realistic operational altitudes and conditions, including the challenge of a moving target. The *Predator B* will also be equipped with a multispectral targeting system for its newest support role: "hunter–killer."

The *DoD* has further expanded the payload options for the *Predator*, demonstrating its ability to launch other, smaller, *UAV*s and deliver weapons just beyond the laser-guided *Hellfire* missile. More specifically, on the initiative of the Defense Threat Reduction Agency (*DTRA*) and the Naval Research Laboratory, the *Predator* can be used as a mother ship to launch other smaller *UAV*s, namely, the *Finder* (flight inserted detector expandable for reconnaissance). The *Finder* is a 57-lb, *GPS*-guided system that can carry different sensors; the *Predator* can carry one *Finder* under each wing. During tests in August 2002 at Edwards AFB, California, the *Predator* launched one *Finder* from 10,000-ft altitude. The flight lasted 25 min, and the aircraft was monitored by the *Predator* ground station. The *Finder* can be equipped with various payloads, including an atmospheric sampling sensor or an imagery sensor to conduct reconnaissance in heavily defended areas prior to attack. The *Finder* is less expensive and harder to detect than the *Predator*, so it could more easily fly into heavily defended areas without incurring a significant loss if shot down.

Since its first flight on July 3, 1994, the *RQ-1A Predator UAV* program reached a major milestone, 50,000 flight hours, on October 26, 2002, during an operational sortie.

In addition to the RQ-1 model, that is used for reconnaissance, there is a multirole Predator designated MQ-1, that is used as an unmanned strike platform. On March 22, 2003, during Operation Iraqi Freedom, the MQ-1 Predator found and destroyed an Iraqi ZSU-23-4 radar guided mobile anti-aircraft artillery gun outside the southern Iraqi town of Al Amarah using an AGM-114K Hellfire II missile.

RQ-4A Global Hawk:

Global Hawk is a high-altitude, long-endurance, unmanned, multiple battlefield applications reconnaissance *UAV*. *Global Hawk* is designed to operate at high altitudes for long periods of time, giving battlefield commanders accurate, near-real-time high-resolution imagery of areas as large as 40,000 square miles (e.g., the size of Illinois). With a 116-foot wingspan, the 44-foot-long 15-foot-high *UAV* can range as far as 13,500 nautical miles up to 65,000 feet mean sea level (*MSL*), gathering vital battle space data. That makes *Global Hawk* the world's most advanced high-altitude, long-range remotely operated aircraft. The *UAV* is designed to have 42-hr endurance with airspeed of approximately 335 knots, and carrying a 1-ton payload, and 900-lb of dedicated communications. (Note that the *Global Hawk* can stay aloft for almost two days). Specifically, the *Global Hawk* has the capability to capture and deliver images from SAR, EO, signals intelligence (*SIGINT*), and *IR* sensors to ground controllers from 65,000 feet with its 48-in K_u-band *Satcom* antenna in all types of weather, day or night. That is, once airborne, it can be controlled from the ground and can see the movements of enemy assets and personnel with startling clarity and near-real time accuracy. The *Global Hawk*'s ground surveillance mission could be expanded to include air surveillance and targeting. Navigation is by *GPS/INS*. Once mission parameters are programmed and loaded into the mission computer, *Global Hawk* can carry out the entire mission autonomously (i.e., the vehicle flies autonomously from take-off to landing). More specifically, the aircraft's "pilots" stay on the ground. Its flight control, navigation, and vehicle management are independent and based on a mission plan. That means that the airplane flies itself: There is no pilot on the ground with a joystick maneuvering it around. However, it does get instructions from airmen at ground stations. The launch and recovery element provides precision guidance for takeoff and landing, using a differential global positioning system (*DGPS*). That team works from the plane's operating base. At another ground station, airmen in the mission control element tell *Global Hawk* where to go and where to point its sensors to get the best images. The *Global Hawk* is being considered to take over the duties of the manned *U-2S* aircraft. The *Global Hawk* entered *EMD* on March 6, 2001. Two production *Global Hawk* aircraft are expected to be delivered to the Air Force by the contractor (Northrop Grumman's Ryan Aeronautical Center) in fiscal 2003. The Air Force is planning a series of upgrades to turn the *Global Hawk* into a true multi-intelligence collector. Modifications will include making wing stations functional for extra payloads, including *SAR* and multispectral sensors.

Specifically, the Block 10 *Global Hawk*'s *IOC* is for the year 2009, and will include a huge array of sensors such as a sophisticated synthetic aperture radar, moving target indicator, electrooptical and infrared sensors, and high-rate satellite and line-of-sight data link systems. To use them properly and gather the best information, it must fly above 40,000 feet. That way the craft can get a good slant range.

Since its first flight in February 1998, *Global Hawk* has flown 74 times, logging a total of 884.7 hours as of April 5, 2001. Currently there are five U.S. Air Force *Global Hawks*. The USAF's *Global Hawk* made aerospace history as the first *UAV* to fly unrefueled 7,500 miles (12,067.5 km) across the Pacific Ocean from America to Australia. Departing from the AF Flight Test Center at Edwards AFB, California, April 22, a *Global Hawk* named *Southern Cross II* flew 23 hours, 20 minutes, and arrived April 23 at 8:40 P.M. local time at the RAAF Air Base Edinburgh, near Adelaide. While in Australia for six weeks, *Global Hawk* will fly 12 missions, demonstrating its ability to perform maritime and littoral surveillance for the RAAF, USAF, Canadian Navy, U.S. Navy and Marine Corps, and U.S. Coast Guard units participating in the allied exercise *Tandem Thrust 01*.

The per-unit cost of a *Global Hawk*, without sensors, is projected to range from $16 million to $20 million.

Dark Star:

The *Dark Star* is a low-observable *UAV*, intended to operate in high-threat environments at altitudes in excess of 45,000 ft for at least 8 hours, 575 miles from the base. Navigation is via *GPS/INS*. Cruise speed is 300 mph with a flight endurance of 12 hours. The vehicle flies autonomously from takeoff to landing, providing near real-time imagery information for tactical and theater commanders. Furthermore, the vehicle was designed to monitor a mission area of 18,500 square miles using a recon/optical *EO* camera or an *SAR*, transmitting primarily fixed-frame images while in flight. This program was terminated in January 1999.

UCAV:

In the spring of 2001, the Pentagon flight-tested the *UCAV* (unmanned combat air vehicle), a bomb-dropping version of the pilotless spy/reconnaissance planes that circled over Kosovo in 1999. Expected *IOC* is for 2010, assuming that Congress allocates the necessary funds for *RDT&E*.

Unlike fighter aircraft that can pull up to 8 *g*'s, the *UCAV* can withstand only 3–5 *g*'s. It uses off-the-shelf engines, sensors, and other parts. Therefore, without a pilot, a *UCAV* would require far less protective gear, avionics, and other pilot-support systems. However, future *UCAV*s are expected to perform maneuvers, such as 18-*g* turns, that human pilots cannot withstand.

The *UCAV*'s primary mission is focused on suppressing enemy air defenses (*SEAD*), that is, take out enemy *SAM*s and other defenses, as well as conducting strike missions. Moreover, controllers, rather than pilots, will monitor as many as four *UCAV*s from a ground station. The *UCAV*s will be programmed to fly a preset flight path or to loiter over heavily defended areas looking for targets. The *UCAV* is the most advanced and futuristic application for *UAV*s that will perform high-risk combat missions. The *UCAV* could be made stealthy and autonomous using inertial guidance.

Most recently, the Air Force's *UCAV* has been redesigned. Specifically, the vehicle will be much larger and heavier than the first design. The redesign is intended to narrow the gap between initial prototypes and an operational system. The first prototype, the *X-45A UCAV* technology demonstration, completed its first flight on May 23, 2002, at Edwards AFB, California, reaching an airspeed of 195 knots at an altitude of 7,500 feet (2,286 meters). The 14-minute flight was a key step in providing a transformational combat capability for the Air Force. Moreover, this first flight successfully demonstrated the *UCAV*'s flight characteristics and the basic aspects of aircraft operations, particularly the command and control link between the aircraft and its mission-control station. A second *X-45A*, the *Red Bird*, is nearly completed and will begin flight test demonstrations in 2003. This will lead to multiaircraft (pack) flight-test demonstrations in 2003. Eventually, *UCAV*s will fly in packs, searching for enemy antiaircraft missile launchers and working together to destroy them under the supervision of a human operator, who, as stated above, could be located anywhere in the world. Beginning in the summer of 2003, into early 2004, demonstrations for weapons delivery will begin. Culminating in 2006, testing will eventually include *UCAV*s and manned aircraft operating together during an exercise. Boeing (the developer of the vehicle) and *DARPA* (Defense Advanced Research Projects Agency) updated the design to prepare for production of the more operationally representative system, the *X-45B*. The *X-45B* will be a fieldable prototype aircraft, laying the foundation for an initial operational system toward the end of this decade. Moreover, the *X-45B* will incorporate low-observable technologies and will be larger and more capable than its predecessor.

The basic concept for *UCAV* will be a four-ship pack under the command of a battle manager, who will have the situational awareness to command and control the vehicles. In the 2007–2008 time frame, the *UCAV* will begin to perform its mission, achieving the preemptive destruction of enemy air defense targets.

In order to improve the aerodynamic performance, the *X-45B*'s wing area and fuselage length have increased. For example, the wing area grew by 63%, and the fuselage, 11%. The total vehicle is now 24% larger. In addition, the redesign increases the length of the *UCAV*'s internal weapons bay by 21 in to 168 in. This should allow the aircraft to carry six *SDB*s internally and give the *UCAV* the same size bay as the *JSF*. Changes also will be made to the propulsion system. The airframe has been expanded to accept a turbofan with a 26-in-diameter fan, versus the 24-in version presently used. The increase should boost the thrust by 7% and elevate the *UCAV* into the 7,000-lb-thrust class. *UCAV*s with early-model directed-energy weapons would target air defense missiles and radar sites.

The U.S. Navy is also exploring the possibility of using *UAV*s. However, the Navy wants a more capable *UCAV* than the Air Force. It is requesting an airborne surveillance capability, in addition to the *SEAD*/strike role. The Navy version would feature conformal apertures operating a *UHF* radar, the same frequency used by the *E-2C*. Furthermore, it would include a narrow-field-of-view *SAR/GMI* radar, which is also on the *USAF* system to refine bombing coordinates and conduct poststrike battle damage assessment. The Navy's air vehicle is expected to have an empty weight of 6,000–12,000 lb. Mission endurance may vary depending on the mission. While a strike mission may last 5–6 hr, a surveillance mission would likely last 9–12 hr. In addition, the Navy is looking into the possibility of first- and second-generation vertical takeoff unmanned aerial vehicles (*VTUAV*). The performance requirements for a first-generation *VTUAV* are modest. With a payload of 200–300 lb, the aircraft is to operate at 6,000 ft and above to provide *LOS* electrooptical data transmission and command and control links. However, the requirements stiffen for generation two, which must deliver antisurface weapons by the year 2020. Specifically, the first-generation *VTUAV*s would add precision targeting for naval surface fires, wide-area data relay, chemical or biological warfare, reconnaissance, and a search capability for combat search and rescue. Second-generation *VTUAV*s, expected to be available after 2012, would add five more capabilities: (a) strike warfare, (b) anti-air warfare detection, (c) offboard mine detection, (d) long-range communications intercept, and (e) overwater search capabilities. It is expected that *VTUAV* requirements will rise rapidly after the year 2010 with increasing deliveries of *DD-21*-class destroyers.

In addition to the *UAV* efforts described above, the U.S. Navy is exploring the possibility of controlling small tactical *UAV*s from submarines for the long-term goal of using them to clandestinely find targets ashore and attack them with cruise missiles. The relatively small 12-ft (3.66-m) wingspan, 100-lb (45.36-kg) vehicle would carry a color video camera to collect imagery that can be transmitted to the submarine by a 100-nm (185.3-km)-range *UHF* data link. Toward this end, the Navy is using on an experimental basis the *Dakota* air vehicle. The *Dakota* is serving as a surrogate air vehicle for a future operational system. The Navy would like to field a submarine-launched, expendable *UAV* that could stay airborne for 12 hr. Moreover, the *Dakotas*, used primarily for reconnaissance, may deploy a network of ground sensors and act as a relay between the submarine and the sensors ashore. The *Dakota* is an autonomous air vehicle using *GPS* guidance and would not have required updates unless commanders wanted to alter the flight plan. Northrop Grumman also is developing a submarine-launched surveillance *UAV* concept. Once a mission plan was uploaded on the *UAV*, the submarine would have been in a receive-only mode in order to avoid detection through its emissions. For a future tactical version, the payload would be refined with a limited automatic target recognition system. Rather than transmitting all video to the submarine, the *UAV* would broadcast imagery only after recognizing a target to reduce bandwidth demands. It would also use digital communications rather than the analog data link used in the demonstration. Finally, in order to preserve covertness, the Navy is willing to make the system expendable.

The U.S. Army is also studying the possibility of using its *Shadow 200* tactical unmanned aerial vehicle (*T-UAV*) for signal intelligence, or *Sigint*. In this initial stage of the program, only an *EO/IR* sensor is considered as a baseline payload. Sensors will be required to collect signals in the 20–2,000-MHz region. Operationally, the *Sigint-UAV* is intended to support brigade commanders. Locating an emitter would be the primary role for the payload. Anticipated *IOC* for the program is in the year 2007.

EADS (European Aeronautic Defense and Space Co.) is studying a design for a *URAV* in the 1,500-kg (3,307-lb) takeoff weight class. The *URAV* will be 5.5-meters (21-ft) long with a 4.1-meter (13.5-ft) wingspan and have low-observable requirements. The *URAV* would operate similarly to a recoverable cruise missile with a data link to a ground control station.

It is conceivable that future strike forces will include a mix of unmanned combat air vehicles and manned aircraft. *UCAV*s offer such strengths as persistence, expandability and stealth.

Miniature Air Launched Decoy (MALD):

DARPA (Defense Advanced Research Projects Agency) is in the process of transferring the *MALD* technology demonstration follow-on program to the Air Force's lethal *SEAD* program office. *MALD* is being developed to provide Air Combat Command with the ability to achieve air superiority by confusing enemy air defense systems. The 91-in (2.31-m) decoy is designed to fly autonomously to simulate the mission profiles of typical fighter aircraft with the ability to maneuver through high-*g* turns, climbs, and dives. *MALD* is equipped with a signature augmentation subsystem, which provides active augmentation to the vehicle's radar cross section across *VHF*, *UHF*, and microwave frequencies to replicate a tactical fighter when viewed by enemy radar systems.

A *MALD* variant (or derivative) is a supersonic miniature air-launched interceptor *(Mali)* to defeat cruse missiles. It is being built by *DARPA*, which also sponsored *MALD*'s development. *Mali* would be cued by a surveillance aircraft, such as an *E-3 AWACS*, which would provide target updates while the interceptor flies supersonically toward a target that could be as far away as 200 nm (371 km). Once close to the cruise missile, *Mali* would activate its *Stinger* seeker and engage the target from the rear at subsonic speeds. (The USAF terminated the *MALD* program in January 2002.)

Other nations are also involved in *R&D* of *UAV*s. For example, Saab Aerospace (Avionics and Dynamics Division) is conducting wind tunnel tests of a low-signature *UAV* designed for attack missions under the framework of Sweden's National

Aeronautics Research Program. Other areas being studied include (a) production engineering, (b) propulsion systems, (c) strength, (d) radar, and (e) *IR* signatures and weapons separation. Finally, *NATO* countries operate a number of *UAV*s such as the *Exdrome* and *Hunter*.

F

Past and Present Tactical/Strategic Missile Systems

F.1 Historical Background

Immediately following the closing phase of *World War II*, and in particular in 1950 with the involvement in the Korean conflict, the United States embarked on a crash program of missile research and development. Some of these missiles, in particular those developed in the years 1950–1964, are listed in Table F.1.

Most of these missiles are no longer in current inventories. They are presented here from a historical perspective. Those that still are in the inventory, for example the *Sidewinder* and *Sparrow III*, have advanced state-of-the-art guidance systems. Therefore, all of the missile programs that have come and gone have served as a basis for the constantly improving research and development programs for the current missiles.

The research program is a continuing process, not only for the production of missiles, but also for the many individual system components. The program of component research is based on realizing major aims and overcoming problems that are inherent in the development of dependable solid-rocket motors that provide reliable high-altitude, supersonic operation.

Some of the earlier (1947–1956) USAF/ARMY guided missile *popular names* are the following:

Guided Missile	*Name*
TM-61B	Matador
SM-62	Snark
GAM-63	Rascal
SM-64	Navaho
SM-65	Atlas
GAM-67	Crossbow
IM-99 (69)	Bomarc
GAR-1	Falcon
SAM-N-6	Talos (Army/Navy)
SAM-A-7	Nike (Army)
SSM-A-17	Corporal (Army).

Table F.1. Missile Development 1950–1964

Missile System and Designation	Guidance System	Propulsion System	Service
TITAN I (*HGM-25A*)	Radio–Inertial	Liquid rocket	Air Force
TITAN II (*LGM-25C*)	Inertial	Liquid rocket	Air Force
ATLAS (*CGM-16D*) (*HGM-16F)*	Radio–Inertial	Liquid rocket	Air Force
MATADOR (*MGM-1C*)	Radar–Command and Hyperbolic	Turbojet	Air Force
MACE (*MGM-13A*)	Map-matching	Turbojet	Air Force
MACE (*CGM-13B)*	Inertial	Turbojet	Air Force
MINUTEMAN (*LGM-30A, B, F*)	Inertial	Solid propellant	Air Force
BOMARC (*CIM-10A*, and *10B*)	Radar–homing	Ramjet	Air Force
FALCON (*AIM-4A, C, E, F*), (AIM-26A, 47A)	Radar and Infrared Homing	Solid propellant	Air Force
GENIE (*AIR-2A*)	Free-flight	Solid propellant	Air Force
QUAIL (*ADM-20C*)	Gyro–autopilot	Turbojet	Air Force
HOUND DOG (*AGM-28*)	Inertial	Turbojet	Air Force
DAVY CROCKET	Free-flight	Solid propellant	Army
ENTAC (*MGM-32A*)	Wire-guided	Solid propellant	Army
HONEST JOHN (*MGR-1*)	Free-flight	Solid propellant	Army
LITTLE JOHN (*MGR-3A*)	Free-flight	Solid propellant	Army
PERSHING (*MGM-31A*)	Inertial	Solid propellant	Army
HAWK (*MIM-23A*)	Radar-homing	Solid propellant	Army
SERGEANT (*MGM-29A*)	Inertial	Solid propellant	Army
SHILLELAGH (*MGM-51A*)	Command	Solid propellant	Army
NIKE-HERCULES (*MIM-14B*)	Command-tracking Radar	Solid propellant	Army
POLARIS (*UGM-27*)	Inertial	Solid propellant	Navy
REGULUS (*RGM-6*)	Inertial	Turbojet	Navy
SUBROC (*UUM-44A*)	Inertial	Solid rocket	Navy
TALOS *ARM* (*RIM-8E, RGM-8H*)	Beam-rider homing	Ramjet	Navy
TARTAR (*RIM-24B*)	Beam-rider	Solid propellant	Navy
TERRIER (*RIM-2E*)	Beam-rider homing	Solid propellant	Navy
SHRIKE (*AGM-45A*)	Radar-homing	Solid propellant	Navy
SIDEWINDER 1-C (*AIM-9D*)	IR homing	Solid propellant	Navy, AF
SPARROW III-6B (*AIM-7E*)	Homing	Solid propellant	Navy, AF
BULLPUP (*AGM-12B*)	Radio command	Solid propellant	Navy, AF
BULLPUP (*AGM-12C*)	Radio command	Liquid propellant	Navy, AF

Tables F.2 through F.7 summarize the development and classification of some of the modern U.S. tactical/strategic guided weapon systems. However, it should be noted that some of these have been phased out and replaced with more advanced state-of-the-art guidance and propulsion systems. Reliability of the guidance systems is always a primary subject for research. The major effort is for improvement of components of inertial systems, microelectronics, star trackers, and radar and infrared homing systems. The introduction of lasers, fiber optics, the global positioning system, etc., opened up a new field for highly accurate guidance systems as demonstrated in *Operation Desert Storm* in 1991, and in Yugoslavia in 1999. For more details on past and present guided weapons, the reader is referred to [2],[3],[4].

Table F.2. Air-to-Air Guided Missiles

Missile System and Designation	Guidance System	Speed	Range	Remarks
Sparrow III (*AIM-7*) Variants: *AIM-7C IOC*: 1958; *AIM-7E IOC*: 1963; *AIM-7F IOC*: 1976; *AIM-7M IOC*: 1983; *AIM-7P IOC*: 1990	Radar-guided. Inverse monopulse semiactive radar homing seeker.	Mach 4^+	30 nm (56 km)	The *Sparrow III* is a radar-guided medium-range *AAM* with all-weather, all-altitude, and all-aspect offensive capability that has been in service for more than 40 years. The missile has been completely redesigned with new and improved guidance, warhead, and longer range.
Sidewinder (*AIM-9*) Variants: *AIM-9A, 9B, 9H, 9J, 9L/P, 9M,* and *9X*.	*IR* homing; *IIR*.	Mach 2^+	10 nm (18.5 km)	The *Sidewinder* is an *AAM* used by many western nations. It is used in the *F-15C, F/A-18*, and *F-14*'s. The *AIM-9X Sidewinder II* is the newest variant of the *Sidewinder* heat-seeking *AAM*; it is a replacement for the *AIM-9M*. The *AIM-9X* is a high-agility *IIR* missile that uses thrust vector control for additional maneuverability instead of tail-control. The *AIM-9X* provides *BVR* and short-range *HOBS* attack capabilities and is designed to work with the *JHMCS*.

(Continued)

Table F.2. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
Phoenix (*AIM-54*) Variants: *AIM-54A IOC* 1974 *AIM-54B* not produced *AIM-54C IOC 1986* *AIM-54C*$^{+}$ *IOC* 1990	Semiactive radar homing for midcourse; pulse–Doppler radar for the terminal phase.	Mach 5	110 nm (204 km)	This is a U.S. Navy *AIM* that is used as part of the *F-14 Tomcat* weapon system.
AMRAAM (*AIM-120*) Variants: *AIM-120A, B*, and *C*	*TWS* multiple target tracking radar; inertial reference before launch; midcourse and terminal phase updates.	≈ Mach 4	40 nm (74.1 km)	The *AMRAAM* is an *AAM* that uses an active radar seeker. *The AIM-120C* is an improved version. An unguided *AIM-120C* missile was successfully tested and launched from an *F/A-22* for the first time on October 24, 2000, at Mach 0.9 and 15,500 ft (4,724 m). The *C* version was developed specifically for internal carriage on the *F/A-22*. Later versions are expected to carry a multispectral seeker to better spot the small radar altimeter and *IR* signatures of stealthy cruise missiles.

Table F.3. Air-to-Surface Guided Missiles

Missile System and Designation	Guidance System	Speed	Range	Remarks
Shrike (*AGM-45A*)	Semiactive radar-homing guidance.	Mach 2	10 nm (18.53 km)	The *Shrike* is an air-to-surface, anti-radar missile, based on the *AIM-7 Sparrow AA* missile. The missile was first used in combat in Vietnam in 1966, and deployed on *F-4Gs, F-16C, D, F/A-18s*, and Israeli *F-4s* and *Kfirs*. The *Shrike* is being replaced by the *AGM-88C HARM*.
Maverick (*AGM-65*) Variants: *AGM-65 A, B, D, E, F* (Navy version) *G, H,* and *K*.	Various variants of the *Maverick* use *TV*-guidance, laser guidance, and *IIR*.	Mach 1-2	3000-ft. to 12 nm (914-m to 22.2 km)	The *Maverick* is configured for antitank and antiship roles.
SRAM I (*AGM-69A*), and SRAM II (*AGM-113*)	Inertial.	Mach 2.5	100 nm at high altitude, 35 nm at low altitude (186 km – 65 km).	The *SRAM*'s payload possesses a nuclear capability. The *SRAM II* was canceled after Congress stopped funding it.
Standard Arm (*AGM-78*) Variants: *AGM-78A, B, C*, and *D*.	Passive radar homing direct and proximity fuzes.	Mach 2.5	18.4–34.8 nm (30–56 km)	This is an air-launched weapon based on the shipboard *RIM-66A SM-1* surface-to-air missile. It was developed to supplement the *AGM-45 Shrike*.

(Continued)

Table F.3. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
Harpoon *AGM-84A/C/D/G R/UGM-84A/C/D/G* (Submarine-launched).	Uses a 3-axis *ARA* (attitude reference assembly) to monitor the missile's relation to launch platform. In addition, it uses a *BOL* when the range to the target is known. Sea-skimming cruise monitored by radar altimeter, active radar terminal homing. Uses an active radar-homing seeker.	Mach 0.85	75–80 nm (139–148 km) 150 nm (278 km for the RGM-84F)	These series of *Harpoons* are long-range sea-skimming antiship missiles; they can be launched from bombers, ships, submarines, and coastal defense platforms. Like the French (Aerospatiale) *Exocet* and the Norwegian (Kongsberg) *AGM-119 Penguin* short-range antiship missiles, the *Harpoon* is a "fire and forget" weapon. In addition to the Navy aircraft, the *Harpoon* has also been deployed from *B-52G* aircraft. (See also Table F.6).
Air-Launched Cruise Missile *(AGM-86B)*	Inertial plus *TERCOM*.	Mach 0.6	1,555 miles (2,502 km)	A small, subsonic, winged air vehicle, currently deployed on *B-52H* aircraft, which is equipped with a nuclear warhead.
Conventionally armed Air-Launched Cruise Missile (*AGM-86C/D*)	GPS/INS	Mach 0.6	1,600 miles (2,574 km)	A nonnuclear version of the *AGM-86B*, the *conventionally* armed *air-launched cruise missile* (*CALCM*) was first used operationally during the Persian Gulf War. The 3,150 lb. *CALCM* has a 2,000-lb high-explosive warhead that throws out a spray of metal balls,

(Continued)

Table F.3. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
				making it most useful for soft targets such as *SAMs*, *SAsM* launchers, radar antennas, and radar command vans. Its accuracy is similar to that of the *Tomahawk*.
HARM (*AGM-88*) Variants: *AGM-88A, B*, and *C*.	All-aspect, passive radar homing. The *AGM-88C Block IV* has a more sensitive seeker.	Mach 2^{+}	10 nm (18.53 km)	The *HARM* was developed as a replacement for the *AGM-45 Shrike* and *AGM-78* standard antiradiation missile (*ARM*). See also Section 3.4.3. An advanced technology demonstration program, called the *AARGM*, will combine a wide-band passive antiradiation multimode seeker with an active *MMW* terminal guidance system and precision *GPS/INS* navigation. The *AARGM* is intended to hit a target after it stops radiating.
AGM-88E	*GPS/INS*	Mach 3.5–4.5	100 miles	The U.S. Navy is developing the *AGM-88E* with a dual mode *AARGM* (advanced antiradiation guided missile) seeker. This includes a *W*-band *MM* wave sensor and greater field-of-regard. The *HARM* upgrade is to include a variable-flow ducted rocket ramjet engine.

(Continued)

Table F.3. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
Hellfire (*AGM-114*) Variants: *AGM-114A, K, L*, and *M*.	Laser-guided. Some *Hellfire* variants use *IIR, RF/IR*, and an *MM* wave seeker. The laser seeker works in conjunction with a laser target designator.	Mach 1.1	4.3 nm (8 km)	The *Hellfire* is a U.S. Army antitank air-to-ground missile launched from attack helicopters (e.g., the *AH-64A* Apaches). A later version, the *Hellfire II*, was developed in 1997 as an antiship missile. It is armed with a blast fragmentation warhead designed for attacks on ships, buildings, and bunkers. The weapon penetrates the target before detonation.
Sidearm (*AGM-122*)	Passive radar-homing with broadband seeker.	Mach 2.5	9.6 nm (17.79 km)	The *Sidearm* is a short-range antiradar missile. It is an inexpensive self-defense missile used by the U.S. Marines, and is used in fixed-wing and rotary-wing aircraft.
Advanced Cruise Missile *(AGM-129A/B)*	Inertial with *TERCOM* updates.	Mach 0.9	$\approx 2,000$ nm (3,700 km)	This is a stealthy, long-range air vehicle, with a nuclear warhead. Deployed on *B-52H* aircraft, it has improved range, accuracy, and targeting flexibility compared with the *AGM-86B*. This program was canceled in Nov. 1991. The *IOC* was scheduled for circa 1992.

(Continued)

Table F.3. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
AGM-130 Variants: *AGM-130A* (Currently in production with an Mk 84 warhead). *AGM-130C* (Currently in production with a *BLU-109/B* penetrating warhead).	*TV* or *IIR*. Later versions include improved *TV* and *IR* seekers, and *GPS/INS* guidance that permit operation in adverse weather and target acquisition.	Subsonic	N/A	This is a rocket-powered air-to-surface missile carried by the *F-15* fighters, and is designed for high-and low-altitude strikes at standoff ranges against heavily defended hard targets. The pilot-guided *AGM-130* weapon, which was used in air strikes against Iraq and Yugoslavia, adds a radar altimeter and digital control system, providing it with triple the standoff range of the *GBU-15*. *IOC* was in 1994.
AGM-142 Have Nap	Inertial with data link, *TV*, or *IR* homing.	Subsonic	50 miles (80 km)	This is a medium-range, standoff air-to-surface guided missile carried by AF heavy bombers (*B-52H*), built by Rafael (Israel). The warhead is a high-explosive, 750-lb-class blast/fragmentation or penetrator. *IOC* was in 1992.
AGM-154 Joint Standoff Weapon (JSOW) Variants: *AGM-154A Baseline* configuration carries 145 *BLU-97A/B* cluster bombs	Tightly coupled *GPS/INS* for midcourse, *IIR* terminal guidance.	Subsonic	17 miles (27 km) from low altitudes; 40 miles (64 km) from high-altitude launch.	This is an air-to-surface guided missile. First in a joint USAF and Navy family of low-cost, highly lethal glide weapons with a standoff capability, usable against heavily defended soft targets (e.g., radar

(Continued)

Table F.3. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
or submunitions, and is intended against relatively *soft* targets. *AGM-154B* is loaded with six *sticks* of *BLU-108/B* sensor-fuzed submunition arrays. *AGM-154C* carries the same *BLU-111/B* 500-lb unitary warhead used in the Mk 82 *iron bombs*.	Tightly coupled *GPS/INS* for midcourse, *IIR* terminal guidance.	Subsonic	17 miles (27 km) from low altitudes; 40 miles (64 km) from high-altitude launch.	antennas, launchers, and control vans). *JSOW* allows for integration of several different submunitions and unitary warheads, nonlethal payloads, various terminal sensors, and different modes of propulsion into a common glide vehicle. *IOC*: Navy 1998, USAF 2000. The *B-2* will use both the *JSOW* with bomblets and a second version with the *BLU-108* antiarmor submunition. The *JSOW* is intended for use in the *F/A-18s* and *F-16* fighters.
AGM-158 JASSM	*GPS/INS, IIR*	Mach 0.6–0.8	300 nm (556 km)	This is a conventional AF/Navy missile program. After previous failures, the missile was successfully flight tested on Nov. 20, 2001, at the Army's White Sands Missile Range. The missile was fired from an *F-16* flying about 15,000 ft at Mach 0.8. New design changes include a new *IIR* seeker, new missile control unit, and the addition of selective availability antijam GPS receiver. The first aircraft to field *JASSM* (or *Jassm*) will be the *B-52* in 2003. The Navy plans to use the missile on the *F/A-18s*.

Table F.4. Surface-to-Air Guided Missiles.

Missile System and Designation	Guidance System	Speed	Range	Remarks
Stinger (*FIM-92*) Variants: *FIM-92A, C*, and *D*.	Proportional navigation, with lead bias all aspect automatic passive *IR* homing.	Mach 1^{+}	3 miles (4.8 km)	The *Stinger* is a U.S. Army shoulder-fired short-range *SAM* with a maximum altitude of 9,840 ft (3,000 meters). *Stingers* of other countries are: The French *Mistral*, and Russian *SA*-7, -14, -16, and -18. (For more information, see Section 4.1.)
Nike Hercules (*MIM-14*)	Command guidance.	Mach 3.65	75 nm (140 km)	This is an Army *SAM* that is no longer in production.
Hawk (*MIM-23*) Variants: *MIM-23B*, and Improved (*I-HAWK*)	Proportional navigation guidance coupled with *CW* and semiactive terminal homing.	Mach 2.5	21.6 nm (40 km)	The *Hawk* is a *SAM* whose *IOC* was in August 1960. The missile can reach an altitude of 60,000 ft. The *Hawk*'s warhead is a conventional *HE* blast/fragmentation with proximity and contact fuzes. The *Hawk* is used by more than 20 foreign nations.
Chaparral (*M48*) (Also designated as *MIM-72C*)	Launched from an *M54* launcher. The launcher has a *FLIR* thermal-imaging system with automatic target tracking and *IFF*. The missile has passive *IR* homing with radar proximity fuze.	Supersonic.	3.2 nm with a maximum altitude of 9,843 ft (3,000 m).	This is a short-range *SAM* system. It is a modified *AIM-9 IR* homing missile. Target acquisition and postlaunch tracking are accomplished by the missile's *IR* seeker, giving it a *fire and forget* capability.

(Continued)

Table F.4. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
Patriot (*MIM-104*) Variants: *PAC-1, 2, 3*	*TVM* terminal guidance; semiactive monopulse seeker.	Mach 3–4	43 nm (80 km)	The *Patriot* is a new generation of medium-to-high altitude *SAM*s developed as an area defense weapon to replace the *Nike–Hercules* missile. The *Patriot (PAC-3)* is commonly classified as an antitactical ballistic missile (*ATBM*) defense system. For more details, see Section 6.9.1.
Sea Sparrow (*RIM-7M*)	Semiactive *CW* radar homing.	Mach 2.5	12 nm (22.24 km)	This is a U.S. Navy surface-to-air missile.
Standard *SM-1*MR (*RIM-66B*)	Semiactive homing (*SAR*).	Mach 2^+	25 nm (46.3 km)	This is a Navy MR (medium range) *SAM* that can reach an altitude of 60,000 ft. It is a replacement for the *Talos*, *Terrier*, and *Tartar* missiles.
Standard *SM*-2MR (*RIM-66C*)	Inertial navigation with 2-way communication link for midcourse guidance from warships; semiactive homing radar.	Mach 2^+	Block I: 40 nm (74 km). Block II: 90 nm (167 km).	This is a Navy vertical launch system intended for the *Aegis* missile system.
Standard *SM*-2ER (*RIM-67A/B*), and *67C/D*.	Inertial navigation with 2-way communication link for midcourse guidance from warships.	Mach 2^+	75–90 nm (139–167 km).	This ER (extended range) version has improved resistance to *ECM*.

(Continued)

Table F.4. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
Standard *SM*-2AER (*RIM-67B*)	Same as *RIM-66C*	-	-	This is the latest variant in the *Aegis Extended Range* (AER) missile program using *VLS*. The Navy is also developing the *SM-3*. This is a ballistic missile interception system as part of the *Midcourse System* (formerly known as Navy Theater Wide) ballistic missile defense program (see also Section 6.9.1).
Rolling Aiframe Missile (*RIM-116*)	The *RAM* switches to *IR* homing during the terminal phase; initially uses *RF* to home on target emissions to point its *IR* seeker at the target. (Passive dual mode *RF/IR* target acquisition.)	Supersonic	N/A	The *RAM* (rolling airframe missile) is a short-range *SAM*. It is a U.S. Navy *fire and forget* missile.

Table F.5. Antitank Guided Missiles.

Missile System and Designation	Guidance System	Speed	Range	Remarks
TOW (*BGM-71*) Variants: *TOW/BGM-71AIOC*: 1970 *ITOW/BGM-71CIOC*: 1982 *TOW2/BGM-71DIOC*: 1984 *TOW2A/BGM-71EIOC*: 1987 *TOW2B/BGM-71FIOC*: 1992	Wire-guided optical semiautomatic *CLOS* and automatic IR tracking. Also, the *TOWs* use thermal night sight and *EM*/optical/magnetic proximity sensor.	Mach 0.8–0.9	2.33 miles (3.75 km).	The *TOW* is the most widely used antitank guided missile. It is fired from rotary-wing aircraft and ground-combat vehicles. Many countries around the world use the *TOW* as a standard antitank weapon. The *ITOW* (improved *TOW*) added a telescoping standoff detonation probe. The *TOW2B* entered service in 1992. The *TOW* was used in Vietnam, *Operation Desert Storm*, and by the Iranian forces against Iraqi tanks during the 1980–1988 *Gulf War*.
Hellfire (*AGM-114A*)	Laser-guided; also using *IIR* and *RF/IR*.	Mach 1.1	4.3 nm (8 km)	See Table F.3 for details.

Table F.6. Antiship Guided Missiles.

Missile System and Designation	Guidance System	Speed	Range	Remarks
Harpoon (*AGM-84*) Variants: *AGM-84A/C/D/G*. *R/UGM-84/A/C/D/G* (Submarine-launched).	3-axis *ARA* to monitor the missile's relation to launch platform.	Mach 0.85	75–80 nm (139–148 km)	For a detailed description of the *Harpoon*, see Table F.3. The *Harpoon* is being improved under the Block 2 effort.
Slam (*AGM-84E-1*)	Variants of the *SLAM* use either single-channel *GPS* receiver, *IIR* seeker, *man-in-the-loop* terminal guidance, 3-axis *ARA*, or terminal homing *IIR* seeker. The *SLAM* navigates to the target area using a preloaded mission profile updated by real-time *GPS* data.	Mach 0.85	60 nm (111 km)	The *SLAM* is a derivative of the *Harpoon*. Used in the *A-6E, F/A-18, F-16*, and *B-52* aircraft.
Slam ER (*AGM-84H*)	Adaptive terrain following, a passive seeker, and precise aim-point control.	Mach 0.90	> 150 nm (278 km)	The air-launched *SLAM-ER*, an evolutionary upgrade to the *AGM-84E SLAM*, is designed to strike high-value fixed land targets, as well as ships at sea or in port. Moreover, the *SLAM-ER* has an improved penetrating warhead to strike its target with precision and lethality. It also has provisions for installation of automatic target recognition. The wings of the *AGM-84H* can be folded so that it can be mounted on the pylon of an *F/A-18E/F Super Hornet* strike fighter.

Table F.7. Surface-to-Surface Ballistic Missiles

Missile System and Designation	Guidance System	Speed	Range	Remarks
ATACMS (MGM-140) Variants: Block 1, 1A, and 2	*GPS/INS*	N/A	Block 1: 89 nm (165 km) Block 1A: 162 nm (300 km) Block 2: 78 nm (144.5 km)	This is a U.S. Army long-range tactical missile for deployment in modified *M270* armored vehicle-multiple rocket launchers (*AVMRL*). *ATACMS* is a semiballistic missile that uses an *M74* warhead. Launch can be as much as 30° off axis. The missile is steered aerodynamically by electrically actuated control fins during descent, modifying the flight path from a ballistic parabola.
Tomahawk (BGM-109A) Variants: *Tactical Tomahawk* (or Block 4)	Uses the global positioning system, inertial and *TERCOM* guidance. Other variants use *DSMAC*, inertial/terminal active radar homing, or inertial/*TERCOM*.	Mach 0.5–0.70	250–1350 nm (464–2500 km)	The *Tomahawk* is a long-range cruise missile that can be launched vertically from both surface ships and submarines against both ships and land targets. Initially known as *SLCM*, the *Tomahawk's* principal roles are antiship, land attack with conventional warhead (*TLAM-C*), and land attack with a nuclear warhead (*TLAM-N*).

(Continued)

Table F.7. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
				The *Block 4 TLAMs* use *GPS* guidance and have an accuracy of 10–15 meters (32–50 feet) CEP.
Minuteman Variants: *Minuteman I (LGM-30A/B)* *Minuteman II (LGM-30F)* *Minuteman III (LGM-30G)*	Inertial guidance with post-boost control and stellar/inertial.	Speed at burnout is more than 15,000 mph at the highest point of the trajectory.	6,950 nm (12,875 km)	The *Minuteman* is a land-based, long-range *ICBM*; it consists of 2 solid-state stages while the third stage is a liquid-propellant using fuel-injection thrust vector control. The *Minuteman* was the first *ICBM* using *MIRV*. The warhead consists of 3 Mk 12/12A *MIRVs*.
Peacekeeper (*LGM-118A*)	Inertial guidance. Stellar/inertial. Advanced inertial reference sphere (*AIRS*) *IMU* developed by Rockwell Autonetics Division. The *MIRVs* are deployed on the ballistic trajectory phase.	N/A	More than 7,000 nm (11,118 km).	The *Peacekeeper* was developed to replace the *LGM-30 Minuteman ICBM*. It is also known as *MX*. This is a 4-stage solid-propellant *ICBM* using *MIRVs* in the post-boost vehicle. The payload of the *LGM-118A* consists of 10 Mk 21 *MIRVs*. The missile can be moved around to protect it from preemptive attack.

(Continued)

Table F.7. *(Continued)*

Missile System and Designation	Guidance System	Speed	Range	Remarks
				The *Peacekeeper* will be scheduled for retirement under the provisions of the *START II* treaty.
Trident I *C-4* (*UGM-96A*)	Stellar-inertial guidance.	N/A	4,000 nm (7,412 km)	The *Trident I* is an *SLBM* ballistic missile. As is the case with the *MX*, the *C-4* uses a *MIRV* payload.
Trident II *D-5* (*UGM-133A*)	Dormant stellar-inertial guidance.	N/A	More than 6,000 nm (11,118 km).	This is an advanced version of *Trident I*, having a *hard target* kill capability.
Titan II First Launch: April 1964 (*NASA's Titan II-Gemini*). *IOC*: Sept. 5, 1988 (USAF). Variants: *TITAN I* *TITAN IVA* *TITAN IVB*	Inertial guidance.	N/A	N/A	A modified *ICBM* used to launch military, classified, and *NASA* payloads into space. The *Titan* family was established in October 1955. It became known as the *Titan I*, the nation's first two-stage and first silo-based *ICBM*.

F.2 Unpowered Precision-Guided Munitions (*PGM*)

In this section we will discuss the role of the precision-guided bomb, or *GBU*-series. Historically, the unpowered *Paveway Bomb Series*, known as *Paveway I, II* and *III PGMs*, is based on the Mk 80 low-drag general-purpose unguided bomb series that was developed in the 1950s (see also Section 5.6). Specifically, the *Paveway* family (or series) consists of electronic guidance units and fin kits that attach to the nose and tail of standard 500-lb (226.8-kg), 1,000-lb (453.6-kg), and 2,000-lb (907.2-kg) conventional Mark-series bombs. The guidance unit includes a control section, computer, and laser detector. All weapons within a *Paveway* series (e.g., all *Paveway IIs*) use the same electronics package, but the wing assembly, canards, and structure are tailored to the particular bomb size. The *Paveway IIs* were designated *GBU-10E/B* (Mk 84), -12E/B (Mk 82), and -16C/B (Mk 83), and *Paveway III* as *GBU-24A/B* (Mk 84) and *GBU-27*. (Note that the *Paveway IIs* are laser-guided bombs.) The lessons learned from the *GBU-10* series and *GBU-15* precision-guided weapons systems assisted in developing the U.S. Air Force's rocket-powered *AGM-130* standoff land-attack missile [3]. (Note that the *AGM-130* is a powered version of the *GBU-15* that has been heavily used against the well-protected portions of the integrated air defense systems of both Iraq and Yugoslavia since the beginning of 1999; the *AGM-130* uses *TV* guidance and has a range of 30 miles; see also Table F.3.)

Among the best known of these *GBUs* (guided bomb unit) is the *GBU-15*. The *GBU-15* glide bomb can be fitted with two types of warheads, either the Mk 84 2,000-lb blast-fragmentation bomb or the *BLU-109* deep-penetrating bomb. The blast fragmentation warhead is used for attacks on conventional buildings, air-defense weapons, aircraft, and radar sites, while the penetrator is aimed at reinforced aircraft hangars, command and control bunkers, and other hardened targets.

During the 1990–1991 Persian Gulf *Operation Desert Storm*, the *GBU-15* glide bomb with *IR* and *TV* guidance was used with great effect by *F-111F* pilots against Iraqi targets. Specifically, during *Operation Desert Storm*, the *GBU-15s* were dropped from *F-111s* destroying targets from a standoff range of 16–20 nm. Given this standoff range, *F-15E Strike Eagle* fighters can launch these glide bombs outside the lethal envelope of most antiaircraft missiles.

Development of the *GBU-15* began in 1974, based on experience gained in Vietnam with the earlier *Pave Strike GBU-8* modular weapon program. As a result of the *Operation Allied Force* in the air war against Yugoslavia, the U.S. Air Force will modify the *GBU*-series of glide bombs to enable them to hit targets through heavy clouds. In particular, the *Enhanced GBU-15* (or *EGBU-15*) air-to-ground guided munitions, applicable to the *F-15E* aircraft, is likely to be the first in a series of inexpensive, rapid-response modifications planned by the Air Force to refit a range of weapons that will allow autonomous launch in all weather conditions. That is, as the first in a series of programs to give laser-guided bombs an adverse-weather capability, the *USAF* has begun equipping the *GBU-15* glide bombs with *GPS*-satellite guidance. The guidance kit, which is similar to those used in *JDAM* (note that the *JDAM* is a low-cost strap-on guidance kit with *GPS/INS* capability, which converts existing unguided free-fall bombs into accurately guided smart weapons, thus improving the aerial capability for existing 1,000- and 2,000-lb bombs) gravity bombs dropped by the *B-2 Spirit* bombers, will allow the *Enhanced GBU-15* glide bomb to strike within a few feet of its aimpoint, even through a heavy layer of clouds. The system uses reference signals provided by the navigation satellites (i.e., *GPS*). The *EGBU-15* successfully completed its first Phase II program weapon drop test at the Eglin AFB range in August 2000. An *F-15E* launched the weapon at 25,000 ft at a speed of 530 knots (roughly 609 mph), 17.8 miles from the target location [1]. The weapon received a significant upgrade in its ability to attack in all weather conditions using the *GPS*. Moreover, the weapon can carry either a 2,000-lb Mk 84 blast fragmentation warhead or a *BLU-109* penetrating warhead, and can be guided by either television or an *IR* seeker. It has a nominal standoff range of 15 nautical miles, the ability to lock on after launch mode, and high precision against critical targets.

Note that the all-weather attack *GBU-32 JDAM* uses *GPS/INS* to home in on its target with a high degree of accuracy (better than 6 meters (19.68 ft)). Each *JDAM* carries a 1,000-lb or 2,000-lb warhead and can destroy or disable military targets within a 40-foot radius of its point of impact. Furthermore, *JDAMs* can be dropped from more than 15 miles from the target, with updates from *GPS* satellites guiding the bombs to their target. A *B-1B* bomber can carry 24 *JDAMs*. The 1-ton *JDAM* can be selected for air-burst, impact, or penetrating mode. A typical *B-1B* mission might involve targets such as airplane shelters, bridge revetments, or command bunkers. The *B-1B's* use of *JDAMs* became operational in 1999 (see also Section 5.12.2).

As mentioned above, the *GPS* is being applied to a broad range of weapons, such as the *GBU-32 JDAM* (see Table F.8). Specifically, the use of *GPS* will improve the overall performance and accuracy of laser-guided bombs; that is, *GPS* will improve its resistance to laser jamming or clouds interrupting the laser beam. The updated *GBUs* can conduct blind bombing against preloaded *GPS* coordinates. For example, if the laser spot disappears because of a cloud cover or is obscured because of jamming, then guidance temporarily reverts to the *GPS* coordinates. In the near future, *JDAMs* will be equipped with an *FMU-152 A/B* turbine alternator and *FZU-55 A/B* fuze mechanism. The fuze and alternator will allow pilots to reprogram the *JDAM* during a mission.

In addition to the *GBU-15*, other candidate weapons include the *GBU-24* (a 2,000-lb, laser-guided bomb used by the *F-15E* and *F-16*), *GBU-27*, and *EGBU-27* (a laser-guided bomb designed for the *F-117A Nighthawk* stealth fighter), and the *GBU-28* (a 5,000-lb bomb designed to penetrate deep bunkers). A variant of the *GBU-24* guided hard-target penetrator bomb, the *GBU-24E/B*, is used by the Navy's *F-14D Tomcats*. The *GBU-24E/B*, a 2,200-lb (998-kg) bomb, adds *GPS* guidance to the existing laser guidance of the Navy's *GBU-24B/B* baseline. Specifically, the *E/B* first heads toward a *GPS* target point, and the laser designator can refine that point or steer the bomb toward a different target. Figure F.1 illustrates a *Paveway III GBU*.

Another type of bomb is the *GAM-113*. The *GAM-113* is a near-precision, deep-penetration bomb. The 5,000-lb *GAM-113* employs a follow-on version of the *GATS/GAM* guidance package now used with *2,000-lb* bombs. The *GPS/INS* tail kit gives the weapon an all-weather, day/night, and launch-and-leave capability, plus a

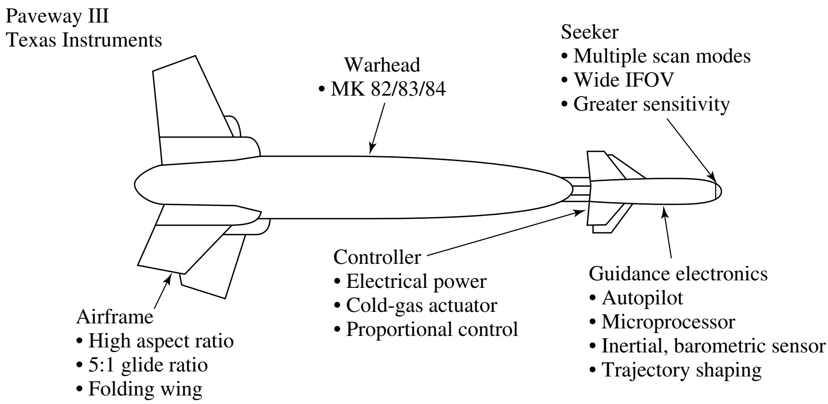

Fig. F.1. Main components of the *Paveway III GBU*.

CEP of less than 20 ft. The *B-2 Spirit* can carry up to eight *bunker-buster GAM-113s*, which are based on the *BLU-113* bomb body. The same device, when mated with a laser-guidance kit, is called the *GBU-28*. At this point, it is worth noting that the *BLU-97* submunitions (or bomblets) have three "kill" mechanisms as follows: (1) a conical charge capable of penetrating 5–7-in armor, (2) a main charge that bursts the case into about 300 fragments, and 3) an incendiary zirconium sponge ring. Table F.8 summarizes some of these guided bomb units [3].

The *Paveways*, however, are not perfect. Clouds, fog, dust, and other weather or battlefield obscurants can interfere with the laser-designation signal, precluding effective *LGB* use. Moreover, laser-guided weapons are only as accurate as the designator's boresighting. For true standoff situations, where an airborne or ground-based designator cannot get near a target, a *GPS*-guided weapon augmented by an *INS* is often better suited than an *LGB*.

At this point, it is appropriate to mention another guided glide bomb, namely, the *AGM-62* Walleye. The *AGM-62* is a *TV*-guided glide bomb designed to be used primarily against targets such as fuel tanks, tunnels, bridges, radar sites, and ammunition depots. The controlling aircraft must be equipped with an *AWW-9B* data link pod.

In addition to the *GPS/INS*-guided weapons, the *LANTIRN* system is used on the Air Force's *F-15E Strike Eagle* and *F-16C/D Fighting Falcon* fighters. The *LANTIRN* system significantly increases the combat effectiveness of these aircraft, allowing them to fly at low altitudes, at night, and under weather to attack ground targets with a variety of precision-guided and unguided weapons discussed in this appendix.

The Army and Navy are developing a 5 × 60-in artillery shell that will home on *GPS* jammers, besides its normal mode of attacking preloaded *GPS* coordinates. The extended-range guided munition (*ERGM*) is a five-year program that started in September 1996. It comes in two versions: (1) the 60-in-long Navy *EX-171*, which includes a solid rocket motor to boost range to 60 nautical miles, and (2) the Army

Table F.8. Guided Bombs

Bomb Series (*GBU*-)	Guidance	Remarks
Paveway II		
GBU-10E/B Mk 84 *GBU-12E/B* Mk 82 *GBU-16C/B* Mk 83	EO. More specifically, bombs of this series have a small seeker; in addition, an optical silicon detector staring array behaves analogously to a monopulse semiactive radar-homing seeker. The latest *Paveway II* series use laser guidance.	2,000-lb class (907.2 kg) 500-lb-class (226.8 kg) 1,000-lb class (453.6 kg) Note: The *GBU-16*, a laser-guided bomb, is built for the Navy by Lockheed Martin.
Paveway III		
GBU-22/B	Laser-homing.	The GBU-22 was a 500-lb class bomb.It was discontinued in the mid-1980s because of technical problems.
GBU-24A/B Mk 84 Variants: *GBU-24E/B*	The *GBU-24* is a laser-guided, low-level, wide area *LGB*. A gimbaled seeker searches for the laser spot. *GPS* and laser guidance.	2,000-lb steel-encased penetrator. Uses a *BLU-109/B* penetrator warhead. A powerful microprocessor allows for land, loft, or dive applications. This is a 2,200-lb bomb used by the Navy in the *F-14D's*.
GBU-27, 27/B	Laser-homing.	Steel-case, 2000-lb bomb delivered by the *F-117A*. Tests have shown that the bomb can penetrate 100 ft (30.5 m) of earth or more than 22 ft (6.71 m) of

(Continued)

Table F.8. *(Continued)*

Bomb Series (*GBU-*)	Guidance	Remarks
		concrete. Used during the 1990–1991 Persian Gulf War. The *GBU-27/B* is *BLU-109/B* compatible.
EGBU-27	Laser-homing and GPS/INS.	The Block 2 *F-117s* upgrade will carry the 2,000-lb *EGBU-27* bomb. The Block 2 will also provide the capability to drop 2,000-lb versions of the *JDAM* with both the penetrator *BLU-109* and the blast/fragmentation Mk 84. In the Afghan conflict the AF used the latest penetrating warhead, namely, the *BLU-118/B*. The *BLU-118/B* penetrating warhead detonates and generates high, sustained blast pressure in a confined space to make the make the munition more effective against tunnels and caves than the *BLU-109* penetrator warhead.
GBU-28A/B	Laser-homing.	This new bunker-busting weapon was developed (and successfully used) for *Operation Desert Storm*, dropped by *F-111s*. *GBU-28s* were also used in Kosovo, dropped by *F-15Es*. The *GBU-28* is a *4,700-lb* (2,131.92-kg) weapon. The warhead used is the *BLU-113/AB* blast fragmentation.
EGBU-28	Laser-homing.	This is an improved, 5,000-lb-class penetrating bomb.
GBU-28B/B	*GPS* and laser homing. It also uses auto *GPS*-aided targeting that updates and refines target information send to the weapon.	The *GBU-28B/B* is an enhanced version of the *GBU-28A/B*, designed specifically for the *B-2*. Testing of the weapon began in March 2003 first with inert and later with live *GBU-28B/B*s. The weapon is deployable in all weather conditions. The program is scheduled for completion by the end of 2004.
GBU-15	Uses *TV* or *IIR* seeker. Targeting options include *LOBL* and *LOAL*.	2,000-lb class bomb. Used against bridges, buildings, bunkers, and chemical plants. Uses a Mk 84 blast/frag or *BLU-109* penetrating warhead. The *IIR* seeker has 90% commonality with the Maverick *AGM-65D*.

Table F.8. *(Continued)*

Bomb Series (*GBU*-)	Guidance	Remarks
EGBU-15	The *EGBU-15* uses *GPS, TV*, laser, and *IR*.	The *EGBU-15* is a 2,000-lb unpowered precision-guided weapon. The *IOC* of the *GBU-15* was as follows: *GBU-15 (TV)*, 1983 *GBU-15 (IIR)*, 1987. The *EGBU-15* underwent successful Phase II tests in August 2000. Its *IOC* is for 2007.
JDAM Series of GBUs		1,000-lb or 2,000-lb class. Low-cost alternative to the cruise missiles. The 1,000-lb *JDAM* blast-fragmentation bomb is accurate to within 36 ft of the target, while the improved *JDAM* is accurate to within 9 ft.
GBU-31	*GPS/INS*	The *GBU-31* uses Mk 84 blast/frag, *BLU-109* penetrator. Standoff range is 15 nm (27.8 km).
GBU-32	*GPS/INS*	The *GBU-32* uses Mk 83 blast/frag, *BLU-110* penetrator. Standoff range is 15 nm (27.8 km).
GBU-35	*GPSINS*	The *GBU-35* uses the Mk 82 blast/frag warhead. Its standoff range is also 15 nm (27.8 km).
GBU-37	*GPS/INS* guided.	This is a 5,000-lb penetrator bomb used against hardened underground targets. It is also known as *GAM-113*. The *GBU-37* was used successfully in Afghanistan against the Taliban.

XM 172 (see also Chapter 1). The *ERGM* is a 12-caliber rocket-assisted projectile carrying a four-caliber submunitions payload to ranges of about 63 nautical miles (117 km), well beyond the range of current Navy gun ranges. The 110-lb (50-kg) aerodynamic projectile is 5 in (13 cm) in length, uses a coupled *GPS/INS* guidance system, and is armed with a submunitions warhead. The *GPS* guidance is tightly coupled to an inertial guidance system that will be immune to jamming, a feature that will enable the *ERGM* round to attack targets in a heavy *ECM* environment. The initial warhead configuration for *ERGM* will consist of 72 *EX-1* submunitions per round. The *EX-1* is a variant of the U.S. Army-developed *M80* dual-purpose conventional munition, which incorporates a shaped charge and an enhanced fragmentation case for use against materiel and personnel targets. The *ERGM*'s submunitions will be uniformly dispensed within a predetermined area that depends upon the specific target to be attacked and the altitude at which the submunitions are released. *ERGM*'s range and precise *GPS* targeting capability will improve naval surface fire support (*NSFS*) and provide near-term gunfire support for amphibious operations, the suppression and destruction of hostile antishipping weapons and air-defense systems, and naval fires support to the joint land battle. Thus, the *ERGM* will allow ships to hit enemy targets deep ashore with concentrated fire, in support of Army and Marine units. Guidance will be provided from an inertial measurement unit (*IMU*). Relying on *GPS* satellites for accuracy, the missile will be launched from shipboard guns. Upon exiting the gun barrel, the missile's' canards and tail fins deploy immediately to control it to an unjammed 20-meter *CEP* accuracy; submunitions can be dispensed at an altitude of 250–400 meters. The *ERGM*, with a short time-of-flight, has $200°/hr$ fiber optic gyros in the Navy version and micromachined silicon gyros in the Army shell.

IOC is scheduled for *FY* 2005 and is to be deployed on later versions of the *DDG-51* Arleigh Burke-class destroyer and the future *DD-21 Land Attack* destroyer equipped with the service's new 5-in/0.62 caliber gun.

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G

Properties of Conics

G.1 Preliminaries

It is well known that when a body is in motion under the action of an attractive central force that varies as the inverse square of the distance, the path described will be a conic whose focus is at the center of attraction. The particular conic (ellipse, hyperbola, or parabola) is determined solely by the velocity and the distance from the center of force. In this appendix, we will consider the purely geometric problem of determining the various conic paths that connect two fixed points and that have a focus coinciding with a fixed center of force. Specifically, in this appendix we will discuss the geometric and analytic properties as applied to ballistic missile trajectories.

There are many equivalent definitions of conics; however, we shall find the following ones most convenient for our purposes [1], [2], [3]:

Ellipse:

The locus of points the sum of whose distances from two fixed points (i.e., foci) is constant.

Hyperbola:

The locus of points the difference of whose distances from two fixed points (i.e., foci) is constant.

Parabola:

The locus of points equally distant from a fixed point (i.e., the focus) and a fixed straight line (i.e., the directrix).

The familiar elements of these conics are shown in Figures G-1, G-2, and G-3.

In Section 6.2, equation (6.1), the general equation of a conic in Cartesian coordinates was given as a second-degree equation of the form [4], [5]

$$Ax^2 + Bxy + Cy^2 + Dx + Ey + F = 0. \tag{G.1}$$

Specifically, any equation of this form with $(A, B, C) \neq (0, 0, 0)$ corresponds to a conic section and vice versa; that is, the coefficients are assumed to be real and $A^2 + B^2 + C^2 \neq 0$. Equation (G-1) can also be expressed as

$$(p^2 + q^2)[(x - \alpha)^2 + (y - \beta)^2] = e^2(px + qy + r)^2,$$

where e is the eccentricity, (α, β) the focus, and $px + qy + r$ is the equation of the directrix of the conic. In *vertex form* the equation is

$$y^2 = 2px - (1 - \epsilon^2)x^2,$$

where $2p$ is the *parameter* of the conic, that is, the length of its latus rectum, which in the ellipse and hyperbola equals b^2/a^2 (where a and b are the lengths of the semiaxes of the conic), and ε is the numerical eccentricity, e/a; there are many other equivalent descriptions. (Vertex is an expression for a conic, obtained by a suitable change of variables, in which the *vertex* is taken as the origin of the coordinate system, and the axis of the conic lies along the x-axis.)

Moreover, the type of conic section is determined by the values of the characteristic equation $B^2 - 4AC$ and the discriminant [5]

$$\begin{vmatrix} A & B/2 & D/2 \\ B/2 & C & E/2 \\ D/2 & E/2 & F \end{vmatrix}$$

of (G-1) is shown in Table G.2. The general quadratic equation is $ax^2 + bx + c = 0$ with solutions

$$x = (-b \pm \sqrt{b^2 - 4ac})/2a.$$

The vanishing of $b^2 - 4ac$, called the discriminant, is a necessary and sufficient condition for equal roots. If a, b, c are all rational numbers, then the roots are real and unequal if and only if $b^2 - 4ac > 0$. At this point, a few words about the discriminant are in order.

The discriminant is an algebraic expression, related to the coefficients of a polynomial equation (or to a number field), that gives information about the roots of the polynomial; principally, the discriminant is nonzero if and only if the roots are distinct. For example,

$$D = b^2 - 4ac$$

is the discriminant of the quadratic equation

$$ax^2 + bx + c = 0;$$

D is positive exactly when the equation has distinct real roots, and is zero exactly when it has equal real roots. More precisely, the discriminant of a polynomial p of degree n over a given field is the quantity.

$$D(p) = (-1)^{n(n-1)/2} R(p, p'),$$

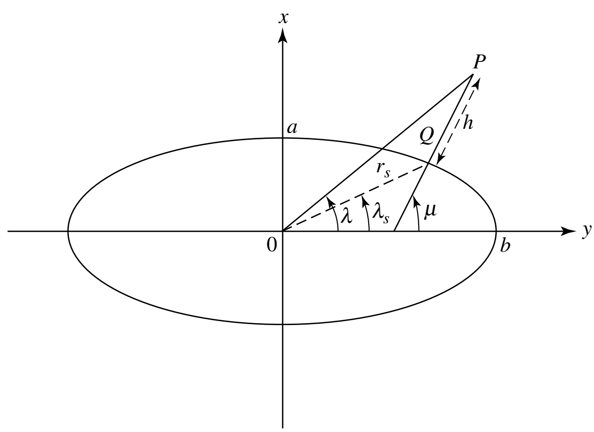
where R is the *resolvent* of p and p'.

Characteristic	Discriminant	Type of Conic
0	$\neq 0$	Nondegenerate parabola.
0	0	Degenerate parabola; 2 real or imaginary parallel lines.
< 0	$\neq 0$	Nondegenerate ellipse or circle; real or imaginary.
< 0	0	Degenerate ellipse; point ellipse or circle.
> 0	$\neq 0$	Nondegenerate hyperbola.
> 0	0	Degenerate hyperbola; 2 distinct intersecting lines.

G.2 General Conic Trajectories

Preliminaries

From the geometry of the ellipse given below,



the equation for the ellipse is given as

$$(x^2/a^2) + (y^2/b^2) = 1, \quad b > a > 0,$$

where the length of the semiminor axis is given by

$$a = b(1 - f),$$

with f being the flattening. From the above figure, we can obtain for the point Q at sea level an equation in terms of the geocentric latitude λ as follows:

$$\tan \lambda_s = (1 - f)^2 \tan \mu,$$

where μ is the geodetic latitude angle. Furthermore, using the polar coordinates (r_s, λ_s) for the point Q we can readily develop an expression for the sea-level radius. Thus,

$$r_s^2 = \{r_e^2/([1 + [1/(1 - f)^2 - 1] \sin^2 \lambda_s)\},$$

where r_e is the radius of the Earth.

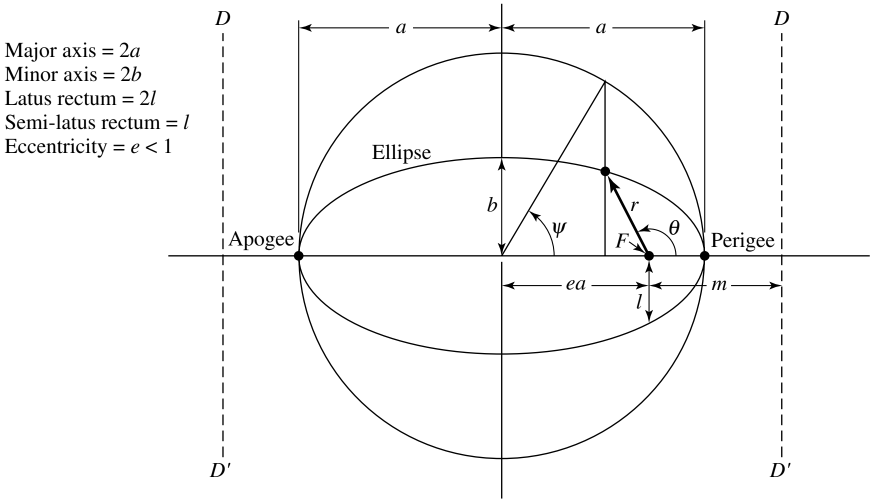


Fig. G.1. Geometry of the ellipse.

Let us now return to the discussion of conics. To recapitulate, a conic is the locus of points whose distance from a fixed point F and a fixed line DD' have a constant ratio e. The fixed point F is called the focus, the fixed line DD' the directrix, and the ratio e the eccentricity. Letting m be the distance from the focus to the directrix DD', the polar equation for the conic is

$$r = e(m - r\cos\theta),$$

or

$$r = em/(1 + e\cos\theta). \tag{G.2}$$

By letting $\theta = 0°, 90°, 180°$, and $\tan^{-1}(b/a)$, important distances are found; see Figure G.1.

Other expressions describing the geometry of the ellipse are as follows:

$$\begin{aligned} r &= l/(1 + e\cos\theta) \\ &= r_p(1 + e)/(1 + e\cos\theta) \\ &= a(1 - e^2)/(1 + e\cos\theta), \end{aligned} \tag{G.3}$$

where $me = l$ (note that in Chapter 6 the letter p was used to denote the semilatus rectum);

Eccentricity:

$$e = \sqrt{1 - (l/a)^2} = (r_a - r_p)/(r_a + r_p), \tag{G.4}$$

$$l = a(1 - e^2). \tag{G.5}$$

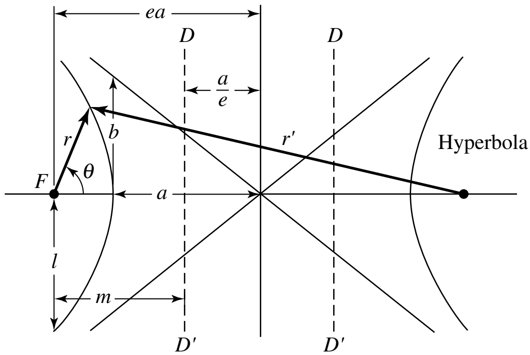


Fig. G.2. Geometry of the hyperbola.

Periapsis radius ($e < 1$):

$$r_p = a(1 - e) = l/(1 + e). \tag{G.6}$$

Apogee radius ($e < 1$):

$$r_a = a(1 + e) = l/(1 - e). \tag{G.7}$$

Major axis ($e < 1$):

$$2a = r_a + r_p = 2l/(1 - e^2). \tag{G.8}$$

Semiminor axis:

$$b = a\sqrt{1 - e^2} = l/\sqrt{1 - e^2}. \tag{G.9}$$

Expressions describing the geometry of the hyperbola are as follows:

$$\begin{aligned} r &= l/(1 + e\cos\theta) \\ &= r_p(1 + e)/(1 + e\cos\theta) \\ &= a(e^2 - 1)/(1 + e\cos\theta), \end{aligned} \tag{G.10}$$

where

$$me = l,$$

$$r_p = a(e - 1), \tag{G.11}$$

$$2a = r' - r, \tag{G.12}$$

$$e = \sqrt{1 + (b/a)^2}, \tag{G.13}$$

$$l = a(e^2 - 1). \tag{G.14}$$

Figure G-2 illustrates the geometry of the hyperbola.

The mathematical expressions describing the geometry of the parabola are as follows:

$$r = m/(1+\cos\theta) = 2r_p/(1+\cos\theta), \tag{G.15}$$

$$m = l, \tag{G.16}$$

$$r_p = l/2. \tag{G.17}$$

Figure G-3 illustrates the geometry of the parabola.

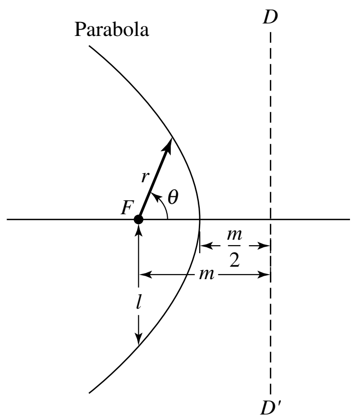


Fig. G.3. Geometry of the parabola.

If $P(r,\theta)$ is any point (or position) on a conic of a planet in its orbit, the radius vector r and the angle θ (measured in the direction of the planet motion) is given by (see (6.2) and (6.21))

$$\begin{aligned} r &= l/(1+e\cos\theta) \\ &= a(1-e^2)/(1+e\cos\theta) \\ &= (h^2/\mu)/(1+e\cos\theta), \end{aligned}$$

where l is the *parameter or semilatus rectum* (that is, l determines the size of the conic), e is the eccentricity (which determines the shape of the conic), μ is the gravitational parameter ($= 1.407654 \times 10^{16}\ \text{ft}^3/\sec^2$; note that in Appendix A the value of μ was given in the metric system), and h is the specific angular momentum given by $h^2 = \mu a(1-e^2)$. Therefore, for motion under the inverse-square control force, the numerical value of e is as follows:

Hyperbola: if $e > 1$,
Parabola: if $e = 1$,
Ellipse: if $0 < e < 1$ (perigee corresponding to $\theta = 0$),
Circle: if $e = 0$,
Subcircular Ellipse: if $-1 < e < 0$ (apogee=point of maximum distance from the origin of r corresponding to $\theta = 0$).

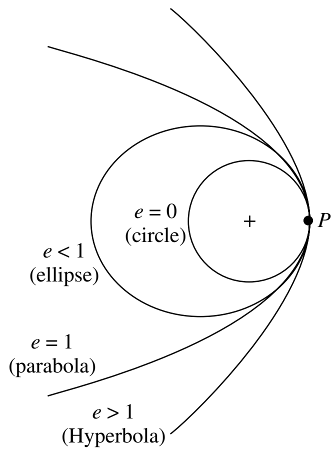


Fig. G.4. Conic sections as gravitational trajectories.

Figure G-4 illustrates the conic sections as simple gravitational trajectories, and as stated earlier, the dimensionless eccentricity e determines the character of the conic section in question. For more information, see Section 6.2.

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H

Radar Frequency Bands

Band Designation	Frequency Range	Typical Usage
VHF	50–330 MHz	Very long-range surveillance.
UHF	300–1,000 MHz	Very long-range surveillance.
L	1–2 GHz	Long-range surveillance, enroute traffic control.
S	2–4 GHz	Moderate-range surveillance, terminal traffic control, long-range weather.
C	4–8 GHz	Long-range tracking, airborne weather.
X	8–12 GHz	Short-range tracking, missile guidance, mapping, marine radar, airborne intercept.
K_u	12–18 GHz	High-resolution mapping, satellite altimetry.
K	18–27 GHz	Little used (H_2O absorption)
K_a	27–40 GHz	Very high-resolution mapping, airport surveillance.
mm	40–100$^+$ GHz	Experimental.

Source: AIAA (American Institute of Aeronautics and Astronautics)

I

Selected Conversion Factors

Length:

1 m = 100 cm = 1000 mm
1 km = 1000 m = 0.6214 statute miles
1 m = 39.37 in; 1 cm = 0.3937 in
1 ft = 30.48 cm; 1 in = 2.540 cm
1 statute mile = 5, 280 ft = 1.609 km
1 nautical mile (nm) = 1852 m = 1.852 km
1Å (angstrom) = 1×10^{-8} cm; 1μ (micron) = 1×10^{-4} cm
1 nanometer (nm) = 1×10^{-9} m

Area:

1 cm^2 = 0.155 in^2; 1 m^2 = 104 cm^2 = 10.76 ft^2
1 in^2 = 6.452 cm^2; 1 ft^2 = 144 in^2 = 0.0929 m^2

Volume:

1 liter = 1000 cm^3 = 10^{-3} m^3 = 0.0351 ft^3 = 61 in^3
1 ft^3 = 0.0283 m^3 = 28.32 liters; 1 in^3 = 16.39 cm^3

Velocity:

1 cm/s = 0.03281 ft/s; 1 ft/s = 30.48 cm/s
1 statute mile/min = 88 ft/s = 60 statute miles/hr

Acceleration:

1 cm/s^2 = 0.03281 ft/s^2 = 0.01 m/s^2
30.48 cm/s^2 = 1 ft/s^2 = 0.3048 m/s^2
100 cm/s^2 = 3.281 ft/s^2 = 1 m/s^2

Force:

1 dyne = 1 gm cm/s^2; 1 newton (N) = 1 kg m/s^2; 1 lb f = 1 slug ft/s^2
1 dyne = 2.247×10^{-6} lb f = 10^{-5} N
1.383×10^4 dynes = 0.0311 lb f = 0.1383 N
4.45×10^5 dynes = 1 lb f = 4.45 N
10^5 dynes = 0.2247 lb f = 1 N
1 kilopond (kp) = 9.80665 N; 1 N = 3.5969 oz = 7.2330 poundals
1 poundal = 0.138255 N

(lb f = pounds force; lb m = pounds mass; N = newton)

Mass:

1 slug = 32.174 lb m
1 gm = 6.85×10^{-5} slug = 10^{-3} kg
453.6 gm = 0.0311 slug = 0.4536 kg
1.459×10^4 gm = 1 slug = 14.5939 kg
10^3 gm = 0.0685 slug = 1 kg
1 kg = 2.2046 lb; 1 lb = 0.4536 kg

Pressure:

1 atm = 14.696 lbf/in^2 = 1.013×10^6 dynes/cm^2 = 1.01325×10^5 N/m^2

Energy:

1 joule = 1 newton meter; 1 erg = 1 dyne cm
1 joule = 10^7 ergs = 0.239 cal; 1 cal = 4.18 joule

Temperature:

0 K = −273.15°C
0°R = −459.67°F
0°C = 32°F = 273.15 K; 100°C = 212°F

$\Theta[K] = \Theta[°C] + 273.15$
$\Theta[°C] = (Q[°F] - 32)(5/9)$
$\Theta[°F] = (9Q[°C]/5) + 32$

Magnitude of degrees: 1 deg = 1°C = 1 K = 9/5°F.

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